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S. W. STRATTON, DIRECTOR

No. 52

ELECTROLYSIS AND ITS MITIGATION

BY

E. B. ROSA, Chief Physicist
and
BURTON McCOLLUM, Electrical Engineer
Bureau of Standards

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By E. B. Rosa and Burton McCollum

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I. INTRODUCTION

In the effort to reduce or eliminate damage to pipe systems and other subsurface metallic structures due to stray earth currents from street railways, a great many methods have been proposed or tried. Some of these have been widely used with more or less benefit in many instances and apparent failure in others. The Bureau of Standards has been engaged for some time past in a general investigation of the subject of electrolysis and its mitigation, the work being carried on by special appropriations granted by Congress for the purpose.

This investigation has included a study of the physical laws governing electrolytic and self-corrosion in soils, an extended investigation of the effects of electric currents on plain and reinforced concrete, and a study of the work of previous investigators relating to the subject of electrolysis and its prevention. Many laboratory investigations have been carried out, and also experiments on artificial pipe lines laid especially for the purpose of permitting experiments under actual conditions with various methods of electrolysis prevention. This work has been supplemented by a large amount of field work in various cities with a view of obtaining first-hand information in regard to the effectiveness of different methods of mitigation as they are commonly applied and to develop methods of making electrolysis surveys and giving any special information desired. The results of these investigations are being published in a number of special reports, a list of which is given at the end of this paper.

The present report is confined principally to a discussion of the subject of the prevention of electrolysis in metallic structures, including gas and water systems and lead-covered cables. The discussion and conclusions presented here are based on the studies above referred to in so far as they yield definite results to the present time. The work is still incomplete, however, and much remains to be done in the investigation of special problems relating to some of the more important methods of electrolysis mitigation. As the work progresses supplementary reports will be made from time to time as the results of the investigation seem to justify.

Although many of the methods of mitigation hereinafter discussed are of limited application, and some of them either worthless or positively injurious, still, in view of the fact that they have been seriously proposed from time to time by engineers of standing, it has been deemed advisable to discuss rather fully the field of usefulness of each particular method, setting forth the reasons for its limitations or dangers, as the case may be. A few of the most important methods, however, have been discussed in detail and a considerable amount of experimental data obtained by the engineers of the Bureau of Standards has been presented as a basis for the more important conclusions and recommendations that are presented in this report.

II. GENERAL CONSIDERATIONS REGARDING ELECTROLYSIS

1. COMPARISON OF THE ELECTROLYSIS PROBLEM IN AMERICA WITH THAT IN OTHER COUNTRIES

Almost immediately following the introduction of electric railways serious trouble from electrolysis of neighboring underground pipes was experienced. This rapid development of acute electrolysis trouble was due mainly to the fact that during the earlier stages of electric railway development relatively little care was taken to maintain good bonding of the rail joints, and as a result of the neglect of this feature it very frequently happened that practically all of the railway return current was compelled to return to the region near the power house by way of the earth, much of it finding its way to the pipes and causing serious corrosion where it flowed again from the pipes into the earth near the power house.

In Great Britain the advent of the trouble was very soon followed by the adoption of somewhat stringent regulations for reducing the damage. These took the form of regulations limiting the voltage drops in the negative return, the most important of which was a rule limiting the voltage drop between any two points in the negative return to 7 volts. The immediate result of this limitation of voltage drop was to bring about better bonding of the track return and the installation of negative return feeders for returning current to the power houses. This was followed by almost complete mitigation of electrolysis troubles, and since that time the electrolysis problem in Great Britain has not been a serious one. More recently the problem has been attacked from a similar standpoint in many cities of continental Europe, and regulations in some respects more stringent than those in effect in Great Britain have been put into effect. As a result very good electrolysis conditions generally prevail in Europe, and in rare instances only has the trouble developed to an acute stage, such as is commonly experienced in this country.

In America, on the other hand, a very different course was pursued. No progress was made toward imposing voltage regulations for the negative return, and although in time more and more attention was paid to track bonding, which retarded the trouble somewhat, the principal reliance from trouble was placed on other methods, one of the most generally used being that known as "pipe drainage." This method of mitigation consists essentially in connecting the underground metallic structures to be protected directly to the rails or railway negative bus by means of copper cables, in all places where the underground pipes or cables tend to become positive to the railway return circuit. This method has been almost universally used by telephone and power companies for the protection of lead cable sheaths, and it has been used to a considerable extent in connection with underground pipes. More recently insulating joints have been used in many installations and this usage is rapidly becoming common practice, particularly with many gas companies, and not a few water companies have used insulating joints with considerable success.

Pipe drainage, however, is a treatment essentially symptomatic in character, this measure being designed to minimize the immediate destructive effects of the stray currents without tending in any way to remove the cause of such stray currents. Notwithstanding the application of these various measures to the pipes, the trouble from electrolysis is becoming increasingly important in this country because of the rapid development of electric railway lines and the increase in traffic, and it is probable that more trouble from this source is now being experienced in this country than anywhere else in the world. Recently, however, this subject has been given more serious attention by the railway companies as well as the owners of underground utilities, and at the present time various national engineering organizations have taken up the matter in a systematic way, and there is reason to believe that substantial progress toward the eradication of this evil will be made in the near future.

2. ELECTROLYTIC CORROSION PROPER

Electrolytic corrosion of underground structures occurs in general wherever current flows from the metallic structure into the earth. The most common cause of these stray currents in practice is primarily the drop of potential in the railway return circuit (proportional to its resistance and to the current flowing in it), as a result of which those portions of the track more remote from the power house will be at a potential above the earth, whereas those portions of the track near the power house will in general be at a potential below that of the earth. In consequence of this, current tends to flow from the tracks to the earth in the more outlying districts and from the earth to the tracks in the region near the power house. These currents after getting into the earth tend to flow as a rule in the general direction of the power house, and they gradually accumulate on any underground pipes and cables that run in the same general direction, but when they reach the region near the power house in which the earth and the pipes embedded therein are at a higher potential than the railway tracks, these currents are again discharged through the earth to the negative railway structure, and it is in this region that the damage to the pipes most frequently occurs.

This region in which the currents are flowing from the pipes into the earth is called the positive area and the outlying region where the currents are flowing from the earth into the pipes is called the negative area. This definition of positive and negative areas is very general, however, and it is not safe to assume that trouble is confined to the so-called positive area. Many places will be found where, owing to high resistance in the joints, the currents will be forced to leak off the pipes and flow through the earth around the joints, thus making a small positive area on one side of the joint and a small negative area on the other side of the joint. Such local positive areas may be found in what is generally known as the negative region, and where these occur corrosion of the pipes may take place although the pipe systems in general are found to be negative to the railway tracks.

Further, two pipe systems occupying the same territory may both be decidedly negative to the railway return, but one more strongly negative than the other. In this case the two pipe systems will be at different potentials and one will discharge current into the other and thus give rise to corrosion on the pipe system at the higher potential, although readings might show that it is at all points negative to the railway return. In determining whether or not a pipe or cable is undergoing electrolytic corrosion it is necessary to determine not only whether it is positive to the railway system but also whether it is positive to any surrounding structure.

When current is discharged from a pipe or cable sheath into the earth the amount of corrosion which take place is roughly proportional to the product of the current strength into the time during which the current flows; in other words, to the quantity of electricity that has been discharged by the pipes. If the structure be iron pipe, the amount of corrosion under most conditions in wet soils will be about 20 pounds per ampere per year, and in the case of lead cables the corrosion will be approximately 75 pounds per ampere per year. In many cases, however, both with iron and lead, either more or less than this theoretical amount of corrosion will take place. This is especially true in relatively dry soils where the corrosion is generally very much less than the figure here given. Extensive investigations have shown, however, that the actual corrosion that takes place in the case of iron varies in different cases from 10 to 25 pounds per ampere per year.

It is not possible, however, to determine the amount of damage to the pipe structure by determining the amount of current which it is discharging from any given portion of its length and calculating therefrom the amount of corrosion which takes place. The reason for this is not alone the uncertainty in the total amount of corrosion just referred to, but more particularly it is due to the fact that the corrosion is in practically all cases very unequally distributed over the surface of the iron, there being a marked tendency for the current to be discharged locally, producing the phenomenon commonly known as pitting. In this manner a small hole may be eaten entirely through the pipe thereby destroying its usefulness, while the average corrosion over the surface of the pipe may be relatively small. Figure 1 shows an example of a pipe that has been corroded by stray currents, and which exhibits the characteristic pitting that has been almost universally encountered.

3. SELF-CORROSION

Self-corrosion is very generally regarded as being due primarily to the presence of local galvanic currents at the surface of the corroded metal, due either to physical differences between adjacent points on the surface of the metal or to foreign conducting substances in the soil. For example, if a piece of carbon in the form of coke be embedded in the soil in contact with the pipe surface at one point there will be a difference of potential between the coke and the pipe and a current will flow from the pipe through the moist soil to the coke and return to the pipe through the contact point between the two. The action here is exactly analagous to the action in a primary battery in which a piece of zinc and a piece of carbon are immersed in the electrolyte and connected together through an external circuit. A current flows through the electrolyte from the zinc to the carbon, thereby corroding the zinc. The electromotive force given by iron or steel when embedded in ordinary soils in contact with coke is usually about 0.6 volt, and this is sufficient to give rise to very rapid corrosion and pitting of the iron surface. Action of this kind is frequently encountered where pipes are embedded in soils containing cinders in which particles of coke may be found.

Galvanic action of this kind also takes place as a secondary action following electrolysis from stray currents. If stray currents are discharged from a pipe producing initial corrosion, the corroded iron thus carried into solution in the soils comes in contact with oxygen dissolved in soil water which results in the precipitation of iron oxide on the surface of the pipe. This iron oxide is a conductor of electricity, and it also exhibits an electromotive force against iron, as in the case of the piece of coke. Hence, where iron oxide is thus deposited on the surface of the iron at any point, corrosion may continue to some extent even though the stray currents which initiated the trouble have been removed. Self-corrosion may also occur from galvanic action due to physical differences between different points of the surface

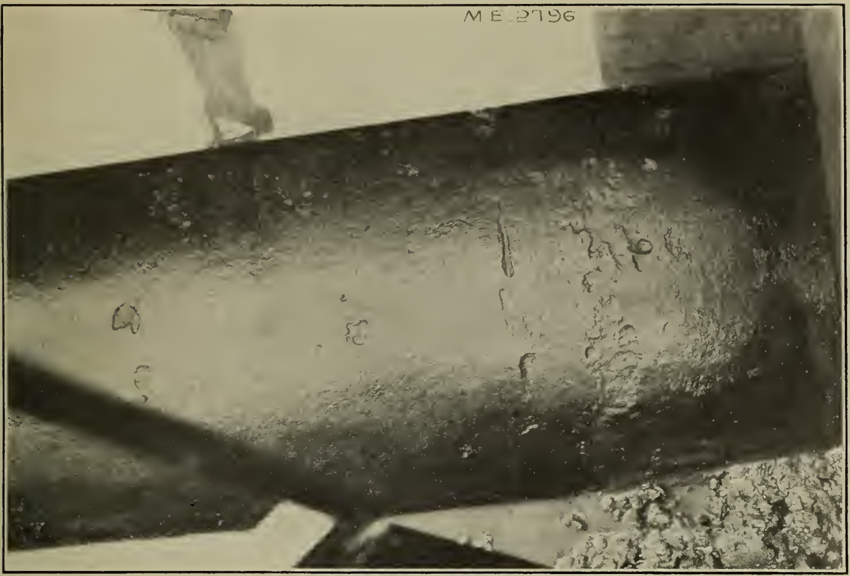

FIG. 1.—*Example of electrolytic corrosion*

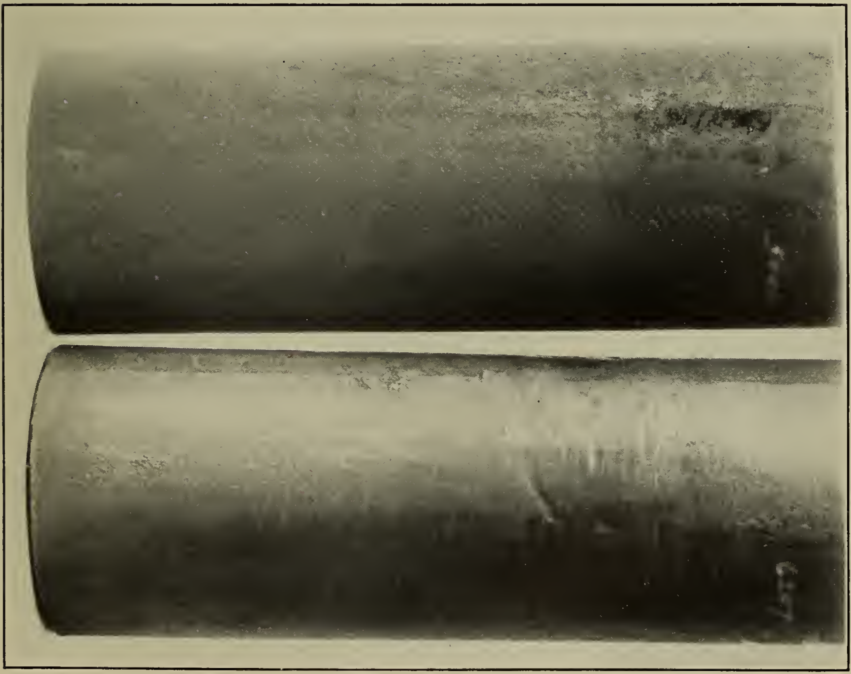

FIG. 2.—*Example of self corrosion*

of the iron itself, or due to differences in the electrolyte in the soil near to adjacent portions of the iron surface.

Unfortunately, self-corrosion generally manifests itself in a manner very similar to that caused by stray currents. This is shown quite clearly in Fig. 2, which is a photograph of two pieces of cast-iron pipe corroded under conditions such that no stray currents could exist. It will be seen that the pipe exhibits pitting very similar to that caused by electrolytic corrosion. Because of this similarity in appearance it is not possible in general to determine by inspection of a corroded pipe whether or not the corrosion was caused by stray currents or by local galvanic action. Owing to this fact it not infrequently happens that cases of pipe corrosion are charged to the railway companies when the damage was actually due to local causes arising from the nature of the soil or of the pipe, or both.

The only sure way of determining whether or not stray currents are causing corrosion in any particular case is by making proper electrical tests to determine whether or not the pipes are actually discharging current into the earth. In a case where serious corrosion has been caused by stray currents and the cause of these stray currents later removed, the only certain way of determining whether or not the previous corrosion was caused by stray currents or by local influences is by making actual corrosion tests in the soil under the same average conditions of moisture and using the same kind of iron as was previously found corroded. In the absence of a test of this kind it is not possible to fix with certainty the cause of the damage.

4. TROUBLES FROM STRAY CURRENTS OTHER THAN CORROSION

While it is no doubt true that by far the greater portion of damage caused by stray currents takes the form of corrosion of underground pipes and cables there are certain other dangers resulting from these stray currents that deserve consideration. Among these may be mentioned overheating of pipes in buildings due to the flow of excessively heavy currents therein. Cases of this kind have been brought to our attention in which service pipes and their connections have been heated to a red heat by stray railway currents flowing through them, and where lead service pipes have been melted off. Such extreme cases are of course rare, but when they do occur the fire hazard accompanying them may at times be serious. Another danger from the presence of stray currents on pipes is that due to the possibility of explosion of gases. Wherever any considerable amount of stray current is found on a gas pipe it is necessary to bond around any contemplated break in the continuity of the pipe, otherwise the arc which would occur between the pipe sections when disconnected would be likely to ignite escaping gas with possibly serious consequences. These various dangers will be referred to again later.

5. ELECTROLYSIS IN CONCRETE AND IN STEEL BUILDINGS [1]

(*a*) *Anode effects.*—During the last few years it has been observed that when an electric current flows through reinforced concrete certain effects are produced which may result in the destruction of the concrete structure. The first of these to be observed is known as the anode effect, first described by A. A. Knudson,[2] which occurs under certain circumstances when current passes from the reinforcing material out into the concrete. The action here is essentially the same as when current is discharged from a pipe into the earth, namely, the surface of the iron is corroded; but the effects of this case are even more serious than in the corrosion of pipes because of the secondary actions which take place.

As soon as iron is carried into solution by the electric current it comes in contact with oxygen in the concrete and there is formed a precipitate of iron oxide. This occupies a volume of about 2.2 times the volume of the original iron, and there results a swelling action which in time may become sufficient to split even very large masses of concrete. The character of the results of this action are shown in Fig. 3, which shows a block of concrete with an embedded iron electrode which has been exposed for some time to the flow of current from the iron into the concrete.

It is very important from the practical standpoint to bear in mind, however, that the disastrous results shown in Fig. 3 occur only under special conditions which are not likely to be frequently

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[1] For a full discussion of the subject of electrolysis in reinforced concrete, see Technologic Paper No. 18 of the Bureau of Standards.

[2] Electrolytic Corrosion of Iron and Steel in Concrete, trans. A. I. E. E., Vol. 26, p. 231, 1907.

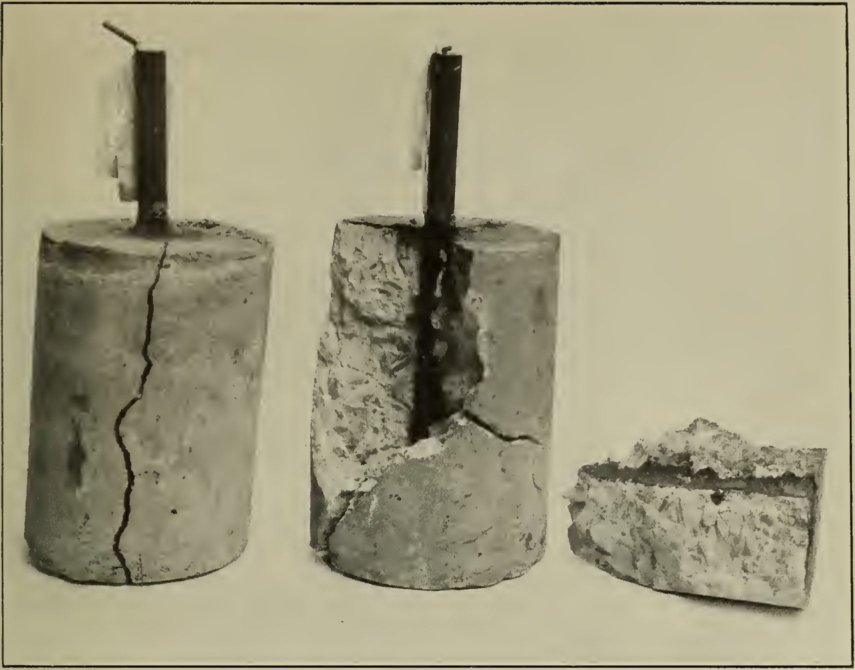

FIG. 3.—*Anode effect in concrete*

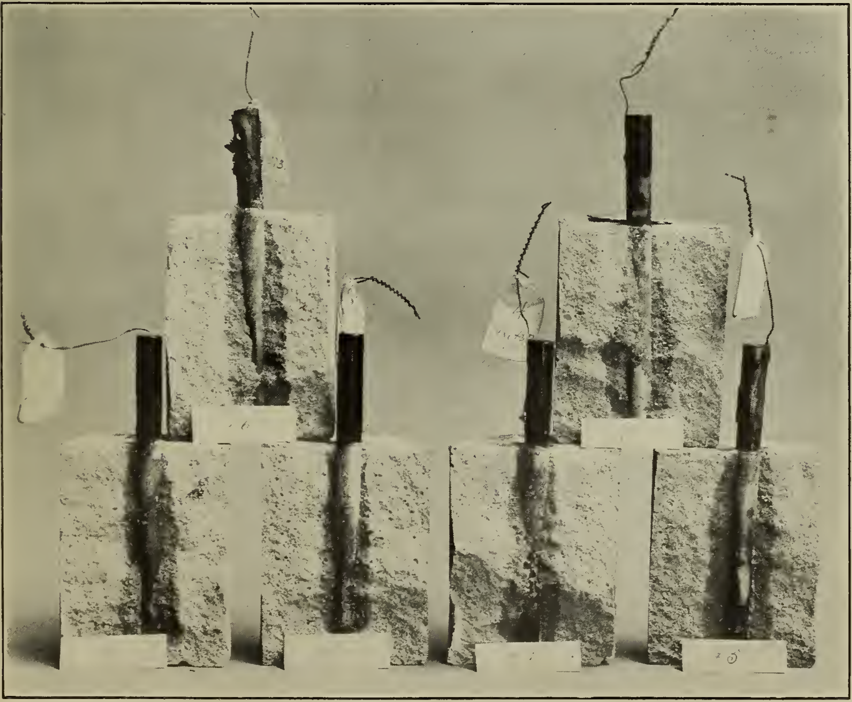

FIG. 4.—*Cathode effect in concrete*

encountered in actual practice. Extensive investigations have shown that in the case of ordinary concrete this rapid corrosion of the embedded iron with the resultant cracking of the concrete takes place only when the potential gradient impressed on the specimen is quite high—much higher, in fact, than would generally be encountered from stray railway currents. If the voltage on specimens of ordinary size such as might be used in buildings is kept as low as 2 or 3 volts or less, long time experiments have shown that practically no damage to the concrete results. It is therefore only under very extreme conditions that serious trouble of this kind is likely to be met in practice. However, it may occur; as for example, when an electric light wire becomes grounded on a metallic conduit embedded in concrete. The voltage here would generally be high enough to cause corrosion of the conduit and any reinforcing material that might be electrically connected therewith, which would result in ultimate splitting and more or less complete local destruction of the concrete structure; this is therefore a danger which under certain conditions should be guarded against. For this reason it may be well not to embed metal conduit in concrete structures where the character of the building is such that this is not necessary, nor should the conduit be electrically connected to the reinforcing material.

It is important to call attention to the fact that while, as above stated, in ordinary normal concrete with only 2 or 3 volts or less acting on concrete structures of the sizes usually encountered in practice, serious corrosion or cracking of the concrete will not occur, such corrosion and cracking will develop if any appreciable amount of salt is added to the concrete either during or after construction. It has been conclusively shown by years of experience that ordinary concrete affords a good protection for iron against natural corrosion, and recent investigations have shown that under ordinary circumstances it also affords a fair degree of protection against electrolytic corrosion. The addition of a small quantity of salt, however, has been found to destroy completely the protective effect against electrolytic corrosion. For this reason it is very important that no salt be used in the erection of reinforced concrete structures wherever there is any likelihood of stray currents from any source getting into the reinforcing material.

(*b*) *Cathode Effect.*—Another effect of electric currents on reinforced concrete has only recently been discovered. This is the cathode effect, and it occurs only where the current flows from the concrete toward the reinforcing material. In this case there is no corrosion of the iron at all, but there is a gradual softening of the concrete at the surface of the reinforcing material, due to the gradual concentration of alkali at the cathode. This softening begins at the surface of the iron and very slowly progresses outward into the concrete, often requiring many weeks or months to progress a distance of a sixteenth of an inch. The practical importance of this phenomenon lies in the fact that the softening of the concrete at the surface of the reinforcing material, although usually confined to a thin layer, is nevertheless sufficient practically to destroy the bond between the iron and the concrete, and in this way a structure may be weakened or destroyed.

The cathode effect has been found to occur not only on high voltages, as in the case of the anode effect above described, but also on relatively low voltages, the rate at which it progresses being roughly proportional to the voltage applied in any particular case. Examples of trouble of this kind are shown in Fig. 4, which shows very definite regions of softened concrete surrounding the embedded iron. Because of the fact that this softening of the concrete near the cathode progresses at a much lower voltage than is generally required to produce the anode effect previously described, this cathode effect is likely to prove of greater practical importance than the cracking of the concrete at the anode which had previously been observed.

In regard to the actual dangers to which reinforced concrete structures in practice are subjected as the result of these phenomena, it should be emphasized that while cases of actual damage of this sort have been encountered in practice in a few instances, they are comparatively rare, and only in exceptional cases have conditions been such as to produce any appreciable amount of damage in actual building structures. We have had occasion to investigate numerous cases in which reinforced buildings or bridges have been damaged in which the damage was attributed to stray currents, but in most cases it has been found that the trouble was not in any way due to the presence of electric currents. In fact only one case has up to the present time come to our attention in which any serious damage to a reinforced concrete structure has occurred in actual practice, except in those instances where salt was present in the concrete in considerable quantity. This emphasizes the importance of omitting salt in the construction of reinforced concrete buildings wherever there is any likelihood of stray currents getting into the structure.

III. METHODS OF MITIGATION APPLICABLE TO PIPES

The various methods of electrolysis mitigation that have been proposed are here treated broadly under two heads—first, those that may be applied to the pipe systems for protection of the pipes without regard to the extent of stray current leaking from the rails; second, those which are applied directly to the negative return of the street railway system and have for their object the prevention of leakage of electric current into the earth or the reduction of such leakage to so low a value that it will do practically no harm.

1. SURFACE INSULATION OF PIPES

Painting or otherwise insulating the surface of pipes, as by the use of treated papers and textiles, was early resorted to as a possible means of protecting the pipes from electrolysis, and this method is still used in some instances. It is doubtful, however, whether there exist any instances in which it has been definitely proven that insulating paints have effectively protected pipes from electrolysis for any considerable period of time, while there are many instances where they have failed utterly and where their presence has actually done harm. This statement may seem somewhat surprising to some who are familiar with instances where paints have withstood the action of soils for a long period and when uncovered both paint and pipe appeared to be in practically as good condition as when they were laid down. Practically all paints are classified as insulators, and it is quite natural that the impression should be more or less prevalent that these paints ought to prove effective as a protection against self-corrosion in the soil. In practice, however, such paints behave in a very uncertain manner at best; a given paint may endure for long periods in some places while in other places in the same city it may deteriorate rapidly and become worthless in a comparatively short time. This is due partly, no doubt, to differences of soil conditions. General failure of these paints under conditions where electrolysis was to be expected indicate that the stray currents have much to do with the destruction of the coatings. With a view to throwing further light on this point and also to determine if possible something of the relative value of these coatings as a possible protection against electrolysis, the Bureau of Standards has carried out a considerable number of experiments with different types of commercial pipe coatings and protective paints which have yielded considerable definite information.

(*a*) *Work of Previous Investigators on Paint Coatings.*—A considerable amount of work relating to surface insulation of pipes has been done by many pipe-owning companies as well as in special investigations by individuals. The most extensive work in this direction carried on by individual investigators was that reported by R. B. Harper before the Illinois Gas Association in March, 1909. In this investigation more than 38 different compounds, including paints, dips, and wrappings, were tested. The conclusions given in the report state that no insulating coating was found that would resist the attacks of electrolysis for any considerable length of time. Against the results of these tests, however, there has been directed a criticism that the voltage used on the coatings was abnormally high (110 volts), and therefore would not represent actual working conditions, where the voltage might average but a few per cent of the above value.

This criticism would appear to be more or less well founded, because it is not desirable as a rule to accept an intensive test as conclusive, and this is particularly true in a case where a breakdown voltage may be involved. It is not safe to assume that because a coating will not withstand the action of 110 volts it is therefore not suitable for insulating pipes at 10 volts or less, and since the voltages to which a pipe coating would be subjected under most practical conditions would not exceed a few volts, tests made on 110 volts would not appear to furnish altogether reliable data as to the value of the coatings as a protection against electrolysis.

In addition to the work mentioned in the previous paragraph that of various other investigators also points to the fact that at least a large proportion of the paints sold for the purpose of preserving metals from corrosion are not impervious to water, and as will be shown later this is a vital point in the protection of pipes from electrolytic corrosion by such means. From the standpoint of soil corrosion the access of a slight amount of moisture to the surface of the iron may not be a serious matter, provided the paint is an inhibitor of corrosion, or at least does not form a galvanic couple with the iron, but if there is a difference of potential of even a few volts between the pipes and soil, the results may be very serious, as shown by the experimental data presented later in this paper.

(*b*) *Materials Available for Insulation of Pipes.*—The materials which are commercially available for this particular kind of insulation work and which are practicable commercially may be divided into four general classes:

(1) Paints or compounds which are to be applied at ordinary temperatures, depending on oxidation or other chemical action, drying, etc., for their setting properties.

(2) Dips or compounds intended to be melted at a high temperature and the iron immersed and left until bath and iron are at the same temperature, when the iron is removed and allowed to cool, the compound hardening with decreasing temperature. These dips include asphalts, coal tar, pitches, and allied products.

(3) Wrappings which consist of alternate layers of compound and fabric, the compounds used including the classes mentioned under both (1) and (2), while the fabric may be either felt, cloth, or paper. These may be treated or untreated, according to the ideas of the manufacturer or the person making the test.

(4) Coverings consisting of some sort of conduit, or a large pipe inclosing the pipe or cable to be protected, the intervening space between pipe and conduit being sometimes filled with an insulating material such as pitch.

(*c*) *Tests on Pipe Coatings.*—Coatings of the first three classes—namely, paints, dips, and wrappings—have been tested in considerable number during the course of these investigations. The details of the experiments thus far completed relating to pipe coverings are reported in full in Technologic Paper No. 15 of the Bureau of Standards, so that only a summary of the results need be presented here.

In making these tests the coatings were carefully applied in accordance with instructions of the manufacturers, and in all cases a sufficient number of coatings were applied to give perfect continuity and insure the absence of pinholes over the entire surface. In order to determine whether or not there were any flaws in the finished coating, the coated surface was immersed in salt water, and an electromotive force of 80 volts was applied between the coated iron and the salt solution for a period of 30 seconds. A very sensitive milliammeter was placed in series with the electric circuit and gave a deflection in case there was a minute flaw at any point of the coating. After 30 seconds the electromotive force was removed and the electrical resistance of the coating measured by a special method. The coating was then placed under a life test by immersing the coated surface in a suitable electrolyte, usually Potomac River water, and impressing on the coating a low potential difference between the iron and the surrounding water. As a rule, five specimens of each kind were used, in two of which the coated iron was made positive and in one negative, and in the remaining two no electromotive force was applied. The electromotive force permanently applied during the life test was 4 volts in all cases for the painted pipes and 15 volts in the case of the dips and wrappings.

Table 1 gives the condensed data for the tests on the pipes covered by paint coatings. This table shows the number of coatings given each specimen, the resistance in ohms per square centimeter before the test was started, the electrolyte used, which in most cases was water from city mains, and the voltage of the time test. The polarity of the coated iron, hours elapsing before the first appearance of current flow in positive, negative, and neutral specimens, and the weeks of drying prior to testing are also given for each specimen.

TABLE 1

Tests of Metal-Preservative Paints as Insulating Coatings

Paint No.	Name of paint	Specimen	Coats	Resis., ohms per cm[a]	Electrolyte	Voltage of time test	Polarity of cone	Hours to failure			Weeks of drying
								Pos.	Neg.	Neut.	
1	Antakwa, heavy	1	4	2.0×10^{11}	2% Na_2CO_3	4	Pos.	312			2
		2	4	2.0×10^{11}	Water	4	Pos.	384			2
		3	4	$>2.0 \times 10^{11}$	do.	4	Neg.		2000		8
		4	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1400	8
		5	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1400	8
2	Antakwa, metal protection.	1	4	2.0×10^{11}	2% Na_2CO_3	4	Pos.	192			2
		2	4	1.6×10^{9}	Water	4	Pos.	0			2
		3	4	$>2.0 \times 10^{11}$	do.	4	Neg.		2000		8
		4	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1400	8
		5	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1400	8
3	R. I. W., number not known.	1	4	2.0×10^{11}	½% H_2SO_4	4	Pos.	312			2
		2	4	$>2.0 \times 10^{11}$	Water	4	Pos.	5000			2
		3	4	$>2.0 \times 10^{11}$	do.	4	Neg.		600		8
		4	4	$>2.0 \times 10^{11}$	do.	0	Neut.			600	8
		5	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1350	8
4	Carbonkote, interior	1	4	3.0×10^{10}	½% H_2SO_4	4	Pos.	528			2
		2	5	3.6×10^{10}	Water	4	Pos.	(a)			2
		3	4	$>2.0 \times 10^{11}$	do.	4	Neg.		(a)		8
		4	4	$>2.0 \times 10^{11}$	do.	0	Neut.			(a)	8
		5	4	$>2.0 \times 10^{11}$	do.	0	Neut.			(a)	8
5	Mindura, brine-resisting finish.	1	5	7.0×10^{9}	3% NaCl	4	Pos.	840			2
		2	5	3.2×10^{9}	Water	4	Pos.	120			2
		3	5	$>2.0 \times 10^{11}$	do.	4	Neg.		760		8
		4	5	$>2.0 \times 10^{11}$	do.	0	Neut.			570	8
		5	5	$>2.0 \times 10^{11}$	do.	0	Neut.			570	8
6	Mindura, ordinary finish.	1	5	10.8×10^{9}	2% Na_2CO_3	4	Pos.	5			2
		2	5	3.2×10^{9}	Water	4	Pos.	7			2
		3	5	$>2.0 \times 10^{11}$	do.	4	Neg.		2000		8
		4	5	$>2.0 \times 10^{11}$	do.	0	Neut.			2800	8
		5	5	$>2.0 \times 10^{11}$	do.	0	Neut.			2800	8
7	Nev-a-Rust	1	4	1.7×10^{9}	2% Na_2CO_3	4	Pos.	5			2
		2	4	7.7×10^{8}	Water	4	Pos.	240			2
		3	4	1.6×10^{9}	do.	4	Neg.		120		8
		4	4	1.6×10^{9}	do.	0	Neut.			336	8
		5	4	2.1×10^{9}	do.	0	Neut.			902	8
8	Carbonall, No. 10	1	4	2.0×10^{10}	½% H_2SO_4	4	Pos.	5			2
		2	4	5.5×10^{10}	Water	4	Pos.	552			2
		3	4	$>2.0 \times 10^{11}$	do.	4	Neg.		3144		8
		4	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1100	8
		5	4	$>2.0 \times 10^{11}$	do.	0	Neut.			1100	8
9	Carbonkote, No. 100.	1	4	3.0×10^{9}	2% Na_2CO_3	4	Pos.	72			2
		2	5	1.6×10^{9}	Water	4	Pos.	1368			8
		3	4	1.1×10^{11}	do.	4	Neg.		6000		8
		4	4	1.1×10^{11}	do.	0	Neut.			2800	8
		5	4	5.5×10^{10}	do.	0	Neut.			2800	8
10	Sarco	1	4	2.0×10^{11}	½% H_2SO_4	4	Pos.	312			2
		2	4	3.4×10^{7}	Water	4	Pos.	0			8
		3	4	9.2×10^{6}	do.	4	Neg.		1752		8
		4	4	1.2×10^{8}	do.	0	Neut.			336	8
		5	4	1.0×10^{6}	do.	0	Neut.			336	8
11	AeOnite, preservative paint.	1	4	4.5×10^{8}	do.	4	Pos.	5			2
		2	4	3.6×10^{8}	do.	4	Pos.	0			2
		3	4	6.2×10^{9}	do.	4	Neg.		2952		8
		4	4	5.4×10^{9}	do.	0	Neut.			336	8
		5	4	5.6×10^{9}	do.	0	Neut.			1208	8

[a] No sign of current after 10,000 hours.

TABLE 1—Continued

Paint No.	Name of paint	Specimen	Coats	Resis., ohms per cm	Electrolyte	Voltage of time test	Polarity of cone	Hours to failure			Weeks of drying
								Pos.	Neg.	Neut.	
12	Crysolite, No. 10	1	4	1.0×10^{9}	Water	4	Pos	0			2
		2	4	6.6×10^{9}	do	4	Pos	240			2
		3	4	$>2.0 \times 10^{11}$	do	4	Neg		860		8
		4	4	1.1×10^{11}	do	0	Neut			1300	8
		5	4	1.1×10^{11}	do	0	Neut			600	8
13	Neponset, Waterdyke paint.	1	4	1.2×10^{9}	do	4	Pos	0			2
		2	5	$>2.0 \times 10^{11}$	do	4	Pos	2800			2
		3	4	1.1×10^{9}	do	4	Neg		10000		8
		4	4	3.5×10^{7}	do	0	Neut			1752	8
		5	4	9.2×10^{8}	do	0	Neut			2376	8
14	No. 107, H. F. Scott	1	4	1.0×10^{10}	do	4	Pos	5			2
		2	4	2.2×10^{9}	do	4	Pos	6500			8
		3	4	1.8×10^{8}	do	4	Neg		912		8
		4	4	6.8×10^{9}	do	0	Neut			912	8
		5	4	2.0×10^{7}	do	0	Neut			3200	8
15	Insulite	1	4	1.0×10^{6}	do	4	Pos	10000			8
		2	5	2.2×10^{9}	do	4	Pos	48			2
		3	4	$>2.0 \times 10^{11}$	do	4	Neg		2700		2
		4	4	4.2×10^{7}	do	0	Neut			336	8
		5	4	1.8×10^{7}	do	0	Neut			336	8
16	Bar-OX	1	4	1.5×10^{9}	do	4	Pos	3300			8
		2	4	1.6×10^{9}	do	4	Pos	816			8
		3	4	1.6×10^{9}	do	4	Neg		206		8
		4	4	3.7×10^{10}	do	0	Neut			700	8
		5	4	3.7×10^{10}	do	0	Neut			1400	8
17	R. I. W., No. 5	1	4	5.0×10^{10}	do	4	Pos	1320			8
		2	4	5.6×10^{9}	do	4	Pos	480			8
		3	4	3.9×10^{9}	do	4	Neg		3900		8
		4	4	$>2.0 \times 10^{11}$	do	0	Neut			1400	8
		5	4	$>2.0 \times 10^{11}$	do	0	Neut			1400	8
18	Gliddens, acid proof and graphite acid proof.	1	4	5.0×10^{10}	do	4	Pos	4500			8
		2	4	2.5×10^{10}	do	4	Pos	5300			8
		3	4	2.5×10^{10}	do	4	Neg		2800		8
		4	4	8.5×10^{10}	do	0	Neut			2880	8
		5	4	1.0×10^{5}	do	0	Neut			2800	8
19	Hydrex, preservative paint.	1	4	4.6×10^{9}	do	4	Pos	2600			8
		2	4	8.4×10^{9}	do	4	Pos	816			8
		3	4	$>2.0 \times 10^{11}$	do	4	Neg		2600		8
		4	4	2.5×10^{7}	do	0	Neut			912	8
		5	4	4.3×10^{7}	do	0	Neut			912	8
20	R. I. W., No. 49, over Tockolith.	1	3	7.2×10^{9}	do	4	Pos	192			8
		2	3	7.2×10^{9}	do	4	Pos	192			8
		3	3	5.6×10^{9}	do	4	Neg		100		8
		4	3	$>2.0 \times 10^{11}$	do	0	Neut			1600	8
		5	3	$>2.0 \times 10^{11}$	do	0	Neut			2000	8
21	Insulate	1	4	$>2.0 \times 10^{11}$	do	4	Pos	100			8
		2	4	$>2.0 \times 10^{11}$	do	4	Pos	1586			8
		3	4	3.1×10^{9}	do	4	Neg		2800		8
		4	4	$>2.0 \times 10^{11}$	do	0	Neut			1200	8
		5	4	4.2×10^{9}	do	0	Neut			900	8
[a]22	Insulator, Carman	[b]1	4	4.0×10^{6}	do	4					
		2	4		do						
		3	4		do						
		4	4		do						
		5	4		do						

[a] Four holes eaten through cone in 48 hours. Ten specimens in all were required to obtain one which would withstand the first test. All were carefully treated and dried 8 weeks.

[b] Nos. 2 to 5 failed on 80 volts.

TABLE 1—Continued

Paint No.	Name of paint	Specimen	Coats	Resis., ohms per cm	Electrolyte	Voltage of time test	Polarity of cone	Hours to failure			Weeks of drying
								Pos.	Neg.	Neut.	
[a]23	Damp-proofer, Carman.	[b]1	4	1.2×10^{8}	Water						
		2	4		do						
		3	4		do						
		4	4		do						
		5	4		do						
24	Crysolite, No. 8	1	4	$>2.0 \times 10^{11}$	do	4	Pos	150			8
		2	4	7.0×10^{8}	do	4	Pos	1032			8
		3	4	1.0×10^{6}	do	4	Neg		120		8
		4	4	1.0×10^{6}	do	0	Neut			1032	8
		5	4	1.0×10^{6}	do	0	Neut			1032	8
25	Dixon's graphite	1	5	9.0×10^{7}	do	4	Pos	48			2
		2	4	3.3×10^{8}	do	4	Pos	2800			2
		3	4	1.6×10^{9}	do	4	Neg		120		8
		4	4	1.6×10^{9}	do	0	Neut			120	8
		5	4	1.8×10^{8}	do	0	Neut			120	8
26	S. P. C., flexible iron paint.	1	4	1.2×10^{8}	do	4	Pos	96			8
		2	4	2.3×10^{7}	do	4	Pos	0			8
		3	4	1.8×10^{8}	do	4	Neg		10000		8
		4	4	1.0×10^{8}	do	0	Neut			672	8
		5	4	2.2×10^{8}	do	0	Neut			672	8
27	P & B, No. 2	1	4	9.8×10^{7}	do	4	Pos	6500			8
		2	4	2.0×10^{8}	do	4	Pos	912			8
		3	4	2.0×10^{7}	do	4	Neg		288		8
		4	4	2.9×10^{8}	do	0	Neut			912	8
		5	4	1.0×10^{4}	do	0	Neut			912	8
[c]28	P & B, black, air-drying varnish.	1	4		do	4	Pos	96			8
		2	4		do	4	Pos	96			8
		3	4		do	4	Neg		96		8
		4	4		do	0	Neut			6500	8
		5	4		do	0	Neut			6500	8
29	National, double K natural graphite paint.	1	4	4.0×10^{8}	do	4	Pos	10000			8
		2	4	3.4×10^{8}	do	4	Pos	10000			8
		3	4	3.4×10^{8}	do	4	Neg		912		8
		4	4	3.4×10^{8}	do	0	Neut			912	8
		5	4	3.4×10^{8}	do	0	Neut			912	8
30	Des Moines, elaterite, No. 40.	1	4	2.7×10^{8}	do	4	Pos	10000			8
		2	4	2.2×10^{8}	do	4	Pos	10000			8
		3	4	1.8×10^{8}	do	4	Neg		120		8
		4	4	6.0×10^{7}	do	0	Neut			2440	8
		5	4	4.0×10^{8}	do	0	Neut			2000	8
31	Des Moines, elaterite, No. 10.	1	4	9.7×10^{6}	do	4	Pos	120			8
		2	4	2.1×10^{7}	do	4	Pos	3300			8
		3	4	4.0×10^{6}	do	4	Neg		120		8
		4	4	1.8×10^{7}	do	0	Neut			96	8
		5	4	9.7×10^{6}	do	0	Neut			96	8
32	I. D. P., steel paint	1	4	4.0×10^{6}	do	4	Pos	120			8
		2	4	6.5×10^{7}	do	4	Pos	120			8
		3	4	6.0×10^{7}	do	4	Neg		120		8
		4	4	5.7×10^{7}	do	0	Neut			96	8
		5	4	1.0×10^{6}	do	0	Neut			96	8
							Av.=	1647	—2900	3112	

[a] Five holes eaten through cone in 48 hours. Ten specimens in all were required to obtain one which would withstand the first test. All were carefully treated and dried 8 weeks

[b] Nos. 2 to 5 failed on 80 volts.

[c] Resistance very low, about 1,000 ohms.

The general appearance of the data under the columns "Hours to failure," which is of course the most important, indicates that a paint is not to be depended upon as a preventive of electrolysis in the presence of moisture, even though the voltage between the pipes and earth be only 4 volts. Here and there an individual specimen appears which seems to have withstood the action of the water for a considerable period of time, and in coating No. 4 only one of the four specimens has been broken down after a little more than a year. It may be said of No. 4, therefore, that it gives far greater promise of good results in practice than any of the others.

The average of the hours to failure seems to indicate that positive specimens lose their insulating power first, with negative specimens second, and those not subjected to a difference of potential third; but the differences are too small to be conclusive on this point. On the contrary, an examination of the data, specimen by specimen, shows quite clearly that the low electric stress applied had very little effect toward reducing the insulation resistance of the paint. The time of the breakdown evidently depends more upon characteristics of the individual specimens than on the action of the water. The manner in which failure of the coating occurred depended upon the direction of current flow.

The anode specimens showed rust spots at the places where the breakdown first took place. These rust spots would grow to craters in some places if the paint coating was brittle and easily broken, or bubbles would form if the coating was elastic. The removal of this crater or bubble would reveal a pit filled with iron rust, the pits in time extending clear through to the sheet iron. The cathode specimens failed in an entirely different way. No rusting of the iron occurred under the paint coating, but gas was liberated, which lifted the film until a blister was formed which would sometimes break and leave a large area of iron exposed. These forms of failure are illustrated in Fig. 5, the specimen on the right being the anode specimens, while the one on the left is a cathode specimen. The specimens having no electromotive force applied showed no deterioration of the coating which was visible to the eye, except in one or two cases where the paint blistered somewhat, as it did when the specimens were made cathode. Coating No. 6 showed this type of failure in the greatest degree.

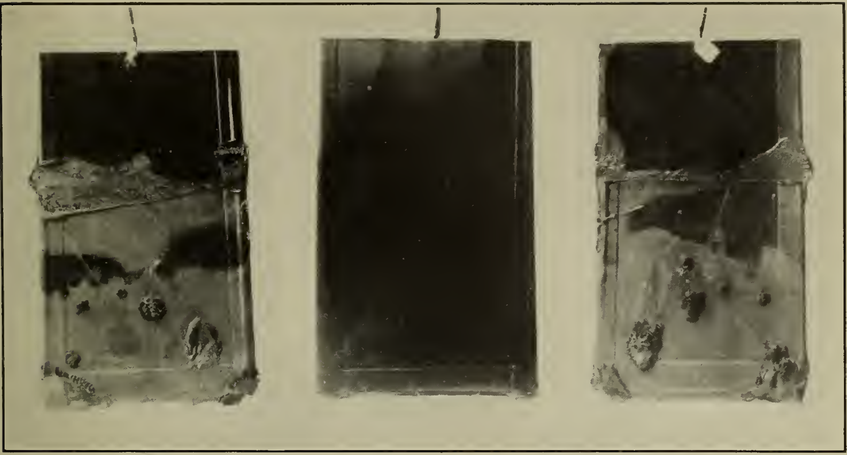

Fig. 5.—*Showing characteristic failure of paint coatings*

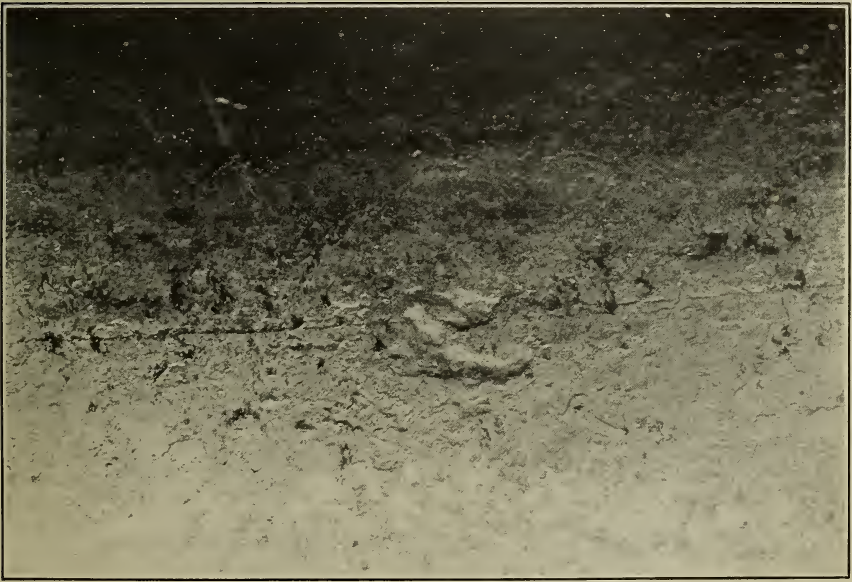

Fig. 6.—*Showing pittings on coated pipes*

It is evident from the rapid failure of practically all of these coatings that they can not be depended upon even for a few months effectually to protect buried pipes from electrolysis due to stray currents.

The tests on pipes covered with dips and wrappings show somewhat more favorable results. The data on these tests are given in the following table:

TABLE 2

Tests of Pipe Wrappings, Dips, Etc., as Insulating Coatings

[Water served as electrolyte in all cases. Voltage=15 except in 1-1 and 4-1 where V=4, and also 206 to 225]

Coating	Material	Layers or dippings	Specimen	Polarity of cone	Hours to failure	
					Positive	Negative
1	Neponset water-dyke felt and compound	3 layers	1	Positive	9200	
			2	do	5040	
			3	do	6000	
			4	Negative		2160
			5	do		9200
2	do	2 layers	9	Positive	7600	
			10	do	4200	
			11	Negative		3600
			12	do		10000
3	do	1 layer	17	Positive	10000	
			18	do	10000	
			19	Negative		3100
			20	do		4200
4	Hydrex felt and compound	3 layers	25	Positive	16000	
			26	do	14700	
			27	do	[a]14000	
			28	Negative		3200
			29	do		5000
5	do	2 layers	33	do		2000
			34	do		2900
			35	Positive	10000	
			36	do	10000	
6	do	1 layer	41	Negative		3040
			42	do		2000
			43	Positive	10000	
			44	do	3800	
7	Pitch and burlap	3 layers	49	do	14700	
			50	Negative		4300
8	do	2 layers	51	Positive	5700	
			52	Negative		5000
9	Barrett specification pitch and tar paper	3 layers	57	Positive	3500	
			58	do	4800	
			59	Negative		3900
			60	do		2100

[a] No failure after the given number of hours.

TABLE 2—Continued

Coating	Material	Layers or dippings	Specimen	Polarity of cone	Hours to failure	
					Positive	Negative
10	Barrett specification pitch and tar paper	2 layers	65	Positive	2100	
			66	do.	2100	
			67	Negative		720
			68	do.		720
11	do.	1 layer	73	Positive	3400	
			74	do.	3400	
			75	Negative		552
			76	do.		48
12	Barrett pitch (sample 1) and muslin	3 layers	81	Positive	12500	
			82	do.	3400	
			83	Negative		3900
			84	do.		3900
13	Barrett pitch (sample 2) and muslin	do.	89	Positive	12500	
			90	do.	12500	
			91	Negative		5500
			92	do.		3400
14	Barrett pitch (sample 3) and muslin	do.	97	Positive	4400	
			98	do.	4400	
			99	Negative		1400
			100	do.		3000
15	Barrett pitch (sample 4) and muslin	do.	105	Positive	12000	
			106	do.	[a] 12000	
			107	Negative		[a] 12000
			108	do.		12000
16	Sarco-mineral rubber-pipe dip and muslin	4 layers	113	do.		2100
			114	do.		2100
			115	Positive	10000	
			116	do.	10000	
17	do.	3 layers	121	Negative		1400
			122	do.		336
			123	Positive	10000	
			124	do.	2100	
18	do.	2 layers	129	Negative		1200
			130	do.		300
			131	Positive	300	
			132	do.	2900	
19	do.	1 layer	137	Negative		2100
			138	do.		300
			139	Positive	300	
			140	do.	2100	
20	Mogul repairing compound and muslin	2 layers	145	do.	1600	
			146	do.	1600	
			147	Negative		1600
			148	do.		1000
21	do.	1 layer	154	Positive	768	
			155	do.	1600	
			156	Negative		1600
			157	do.		1000

[a] No failure after the given number of hours.

TABLE 2—Continued

Coating	Material	Layers or dippings	Specimen	Polarity of cone	Hours to failure	
					Positive	Negative
22	S. P. Co. cold cementing compound and treated burlap	3 layers	162	Positive	7200	
			163	do	[a] 7200	
			164	Negative		7200
			165	do		7200
23	do	2 layers	170	Positive	[a] 7200	
			171	do	7200	
			172	Negative		480
			173	do		7200
24	do	1 layer	178	Positive	[a] 7200	
			179	do	[a] 7200	
			180	Negative		7200
			181	do		[a] 7200
25	S. P. Co. cementing compound (grade A) and treated burlap	3 layers	186	Positive	[a] 7200	
			187	do	[a] 7200	
			188	Negative		[a] 7200
			189	do		[a] 7200
26	do	2 layers	194	Positive	[a] 7200	
			195	do	[a] 7200	
			196	Negative		[a] 7200
			197	do		[a] 7200
27	do	1 layer	202	Positive	[a] 7200	
			203	do	7200	
			204	Negative		[a] 7200
			205	do		7200
28	Sarco-mineral rubber-pipe dip	2 dippings	206	Positive	24	
			207	do	5	
			208	do	96	
			209	do	9000	
29	Barrett pitch (sample 1)	do	210	do	0	
			211	do	0	
			212	Negative		360
			213	do		0
30	Barrett pitch (sample 2)	do	214	Positive	336	
			215	do	0	
			216	Negative		0
			217	do		1056
31	Barrett pitch (sample 3)	do	218	Positive	672	
			219	do	4400	
			220	Negative		1680
			221	do		4400
32	Barrett pitch (sample 4)	do	222	Positive	0	
			223	do	6000	
			224	Negative		672
			225	do		336
33	Minwax and cloth	2 layers	226	Positive	[a] 3192	
			227	do	[a] 3192	
			228	Negative		[a] 3192
			229	do		[a] 3192

[a] No failure after the given number of hours.

It is seen from this table that 82 per cent of the total number of specimens under test had failed after the tests had been in progress about 7200 hours. Coatings Nos. 25, 26, and 33 seem to remain intact, but they were among the last ones put in circuit, so their behavior had not been definitely determined when it became necessary to discontinue the tests. No. 27, however, which is of the same material as 25 and 26, shows two individual specimens which have broken down. These are of one layer of compound and burlap, and it seems reasonable to say that they forecast the future behavior of the others of the same material, but having a greater number of coatings. The results taken as a whole do not indicate that the life of insulating coatings of this character can be expected to be more than two or three years, even when carefully put on the pipes and buried in perfect condition; in most cases failure may be expected to occur within a few months.

The attempts to dip specimens appear to have yielded very poor results, and it is questionable whether coating pipes in this way is any better than painting. The manner of failure of the coatings was similar to that of the paint coatings described above. Failure of the covering was much slower than in the case of the paint coatings after the first appearance of current flow. This is probably due to the greater thickness and rigidity of the coatings.

The characteristic failure of the coating is very strikingly shown in Fig. 5. Explanation of the phenomenon lies in the fact that none of the paints tested are absolutely impervious to moisture, and when they are brought into the presence of water a slight trace of moisture ultimately permeates the coating. When this occurs at any point the coating becomes slightly conducting, and if an electromotive force is applied, a trace of current flows; this gives rise to slight electrolysis, which is accompanied by the formation of more or less gas beneath the coating.

As a rule much more gas is formed if the iron surface is cathode than if anode, so that when current once begins to flow the formation of craters or bubbles in the coating takes place more rapidly if the iron be negative than if it be positive. As this gas increases in volume and expands, the coating is ruptured, after which the current flow is greatly increased at the point of breakdown; in case the pipes are positive rapid electrolysis of the exposed portion follows. In some cases if the coating is sufficiently porous to permit the gases to escape they remain intact and electrolysis may continue beneath the coating, eating through the metal with little or no superficial evidence of failure of the paint. This phenomenon is frequently observed in pipes in actual practice.

The vital weakness of all paints and wrappings thus far tested is due to the fact that they are not entirely nonabsorbent. If a paint could be secured which is absolutely impervious to soil moisture and which would remain so for an indefinite period of time, it would prove an effective preventive of electrolysis; all efforts to produce such paint should be directed to this one end of making it absolutely and permanently moisture proof.

A considerable number of tests were also made on wrapped pipes buried in earth. A number of these pipes were coated by a method in use by a gas company in a large western city, and the specimens actually tested were supplied by the company in question. A considerable number of others were supplied by a large manufacturer of iron and steel pipe, the coatings having been put on primarily for the purpose of reducing soil corrosion. When the pipes were removed from the earth after the test and the wrappings stripped off they were found to be covered with rust spots and here and there were pits of considerable depth. An illustration of these pits is given in Fig. 6. The pipe longest in the ground had been buried about one and a half years, and in that time pits were formed extending almost through the iron. The currents were not large, but the high-current densities resulting from the local failure of the coating resulted in very rapid corrosion of the iron wherever a failure occurred. The test voltage on these buried pipes was about 4½ volts, a voltage of the order of magnitude frequently encountered in practice.

The protection of pipes by laying them in conduit filled with pitch would appear to be effective for a much greater length of time, and in special cases this method would be useful; but the expense would be high if used on a large scale, and at present it appears very questionable whether or not the protection secured would be worth the cost. A large amount of work needs to be done in this direction before definite results on this subject will be available. As far as paints, dips, and wrappings are concerned, however, there can be no question but that as they are at present applied they are not only of no value when applied only in the positive areas, but they may do actual harm by concentrating the current discharge on a comparatively small portion of the pipe surface, thus giving rise to rapid pitting. On the other hand, such coatings are unquestionably of great value in preventing self-corrosion in the case of pipes not subject to electrolysis from stray currents.

Further, in cities where electrolysis is taking place, if such coatings are placed on the pipes in the negative or neutral areas, they would not only protect against self-corrosion, but owing to the increased resistance between pipes and earth the current which would be picked up by the pipes would be greatly reduced, and electrolysis in the remote positive areas would be correspondingly reduced. It may be said, therefore, that such coatings should never be used in the positive districts where the pipes tend to discharge current into the earth; but they may, if circumstances justify, be applied in the neutral or negative areas. However, for reasons pointed out later in this report, such protection from electrolytic corrosion as might be obtained by the use of these coatings in negative areas should be regarded as of an auxiliary character, to be ultimately superseded by more effective mitigative measures along the lines suggested in a later part of this paper.

2. CHEMICAL PROTECTION

The corrosion of iron due to discharge of electric current is dependent not alone on the amount of the current discharge, but also to a very large extent on the chemical nature of the medium into which the discharge takes place and on a number of other factors. The results of a great many experiments carried out by the Bureau of Standards[3] show that in case of ordinary street soils the amount of corrosion of iron per ampere hour varies considerably with the chemical composition of the soil and also with the physical properties of the soil, such as moisture content, temperature, density, etc.

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[3] Burton McCollum and K. H. Logan, "Electrolytic Corrosion of Iron in Soils," Technologic Paper No. 25.

Certain chemicals, as, for example, soluble hydroxides, tend to render iron passive—that is, prevent the corrosion of iron when it is made anode—whereas other chemicals, particularly the chlorides and sulphates, have the opposite tendency. Partly as the result of such opposing tendencies the "coefficient of electrolytic corrosion," or amount of corrosion of the iron which actually takes place in a given soil expressed as a fraction of the theoretical amount, according to Faraday's law, varies between wide limits. Moderately strong solutions of sodium, potassium, or calcium hydroxides alone will entirely prevent the corrosion of the iron by electric currents, and attempts have been made to prevent electrolysis under practical conditions by this means. Sodium and potassium hydroxides are obviously not well suited for this purpose because of their great solubility, which would cause them to diffuse and disappear very quickly. Calcium hydroxide or ordinary hydrated lime is much less soluble, and a soil thoroughly saturated with lime will remain so for a considerable length of time unless soil conditions are such that an abnormal amount of seepage occurs. This material has therefore been used in the attempts that have been made to prevent electrolysis by this method. We have found, however, that while a saturated solution of lime will, when practically pure, completely prevent electrolysis with ordinary current densities, it loses its power entirely when mixed with any considerable amounts of certain salts, such as chlorides, sulphates, carbonates, etc., which occur to a greater or less extent in practically all soils, and which always tend to concentrate about an electrode discharging current into the soil. The protection afforded to pipes by laying them in lime, therefore, is of a transient character, and with the diffusion of the earth salts into the lime its protective property ultimately disappears. The temporary protection afforded by this means is too short lived to justify the expense of its application, except, perhaps, in very special cases where conditions are peculiarly suited to its use.

3. CEMENT COATINGS

Cement coatings have been used on pipes for many years, and the claim has been made, and is still made, by certain manufacturers of cement-lined and cement-coated pipes that their product is immune from electrolysis. In so far as we have been able to observe, however, in all those cases in which these pipes have withstood moderately severe electrolysis conditions without injury for any considerable length of time the pipes have also been laid with cement joints, and it appears certain that the immunity which has been claimed for these pipes has been due to the high resistance joints rather than to the cement coatings. This conclusion is borne out by the results of tests which we have made on experimental lines of these cement-covered pipes on the grounds of the Bureau of Standards. Two experimental lines of these pipes were laid 20 feet apart, one being laid with calked lead joints and the other with cement joints. These were subjected to identical conditions, such as would under ordinary conditions give rise to considerable electrolysis. After about two years excavation revealed the fact that the line having lead joints had already suffered considerably from electrolysis, while the one having cement joints showed practically no evidence of trouble.

From theoretical considerations we might expect that a cement covering would exert a temporary protective influence, since the cement contains a considerable amount of lime, and, as pointed out above, this has a tendency to prevent corrosion of the iron. In fact we have repeatedly demonstrated that iron pipes embedded in cement and kept free from contaminating influences will not corrode to any great extent, even when discharging current at densities which are usually found in the case of underground pipes in practice. When, however, a pipe is covered with a layer of cement an inch or so in thickness and buried in the earth, it requires but a comparatively short time for the earth salts to diffuse into the cement, particularly if the pipes be discharging currents into the earth. This migration of the negative ions into the cement is due largely to the flow of electric current, the negative ions migrating in all cases in the opposite direction from that in which the current is flowing.

As a result of this entrance into the cement of the acid radicals contained in the soil, the protective effect of the calcium hydroxide is in time destroyed.

It has been claimed by some that the resistance of a cement coating is enough higher than the resistance of earth to bring about a material reduction in the current flow to and from the pipes. Our experiments regarding this point do not, however, bear out this claim. We have found that the specific resistance of water-soaked cements, mortars, and concrete will vary as a rule from 2,000 to 8,000 ohms per centimeter cube, which is but little greater than the average specific resistance of a large number of samples of soil obtained from a number of widely scattered cities throughout the country. Further, experiments described, in Technological Paper No. 18 of the Bureau of Standards show that if a small amount of corrosion occurs under the cement coating the expansive forces which develop will shortly cause cracking and splitting off of the cement. We are, therefore, convinced that the protective effect of cement coatings, like that obtained by burying pipes in lime, is but a temporary one and can not be seriously considered as a practical means of permanent electrolysis mitigation.

4. CATHODIC PROTECTION

Since corrosion of pipes occurs only where the current flows from the pipes into the earth, it is obvious that if we could devise some means of always maintaining the pipes negative to the earth at all points of the system electrolysis could not occur. A great many attempts have been made to utilize this principle, and a number of patented methods of electrolysis prevention are based upon it.

Broadly speaking, the principle of cathodic protection involves also another factor in addition to keeping the current always flowing toward the pipes. In some systems where this protection has been proposed, efforts have been made to produce and maintain a passive state of the iron by the production and concentration of alkali, which, under certain circumstances, takes place at a cathodic surface. One method that has been proposed for accomplishing this consists essentially in impressing an unsymmetrical alternating current on the pipe system in such a way as to make the average unidirectional current approximately zero. Under certain soil conditions this alternating current will produce a strong hydroxide solution in the soil adjacent to the pipes, which would tend to produce a passive condition of the iron, tending to protect it from corrosion.

The objections to this latter system are several. In the first place the apparatus required for automatically maintaining a proper unsymmetrical alternating current flow into the pipes involves considerable complication and expense. In the second place it is only under certain soil conditions that a sufficient amount of alkali could be produced to induce the passive state in the iron, and consequently in most cases protection by this method would not be had. In the third place even if those conditions under which strong alkalinity in the soil could be produced, a serious danger would be introduced because of the tendency of such alkaline soils to attack lead service pipes forming a part of the system, or the lead sheaths of power and telephone cables. We have no hesitation in saying that the system would not only be ineffective in most cases but would actually become a menace in others, and it is therefore not to be considered seriously as a means of electrolysis mitigation.

Another method of applying cathodic protection, and the one most commonly thought of when such protection is proposed, consists in connecting a low-voltage generator between the pipe system to be protected and the adjoining rails in each positive area, and so exciting this generator as to maintain the pipes always at a lower potential than the rails. This is very closely related to certain forms of the common pipe-drainage system described below and possesses all of the disadvantages of the latter together with the additional drawbacks of extra expense and complication. At the same time it appears to offer no material advantage over the usual types of pipe-drainage system.

A patented modification of the above method that has been developed abroad consists in substituting a large metallic electrode buried in the earth for the tracks as the positive electrode, the pipe system being as before maintained negative to earth. This plan of substituting a buried electrode for the tracks as the positive terminal has two marked disadvantages, namely, the increased cost of providing the electrode and the relatively small radius of the protected zone. Experiments carried out by us show that the extent of the region protected depends very much on the size of the buried positive electrode and also to a large extent on its position with respect to the pipe system.

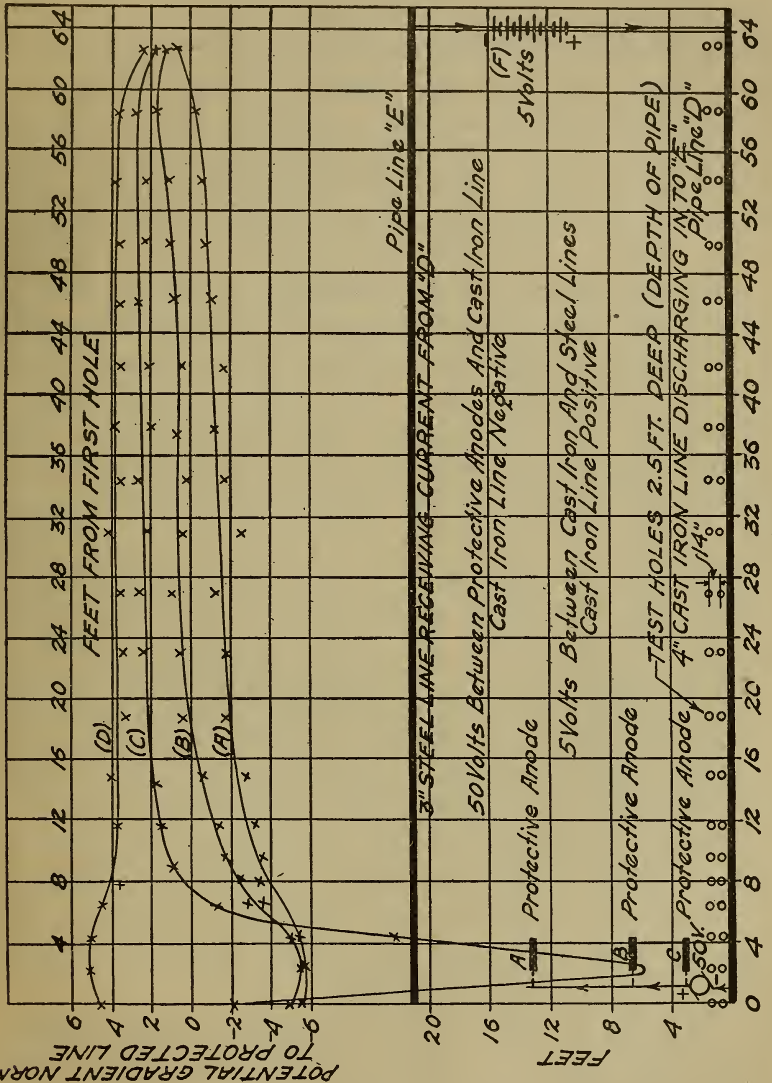
Figure 7 shows in diagrammatic form a layout of experimental pipe lines used for studying this problem. Two parallel pipe lines (*D* and *E*, Fig. 7) were buried about 20 feet apart, one of 4-inch cast-iron pipe and the other a 3-inch steel pipe. Between these pipe lines a 5-volt battery, *F*, was connected in such a way as to make the cast-iron pipe positive, so that it would tend to discharge current into the earth and thence to the steel pipe. A motor generator set was then connected between the pipe line *D* and one of the small buried electrodes *A*, *B*, *C*, the connection being such as to cause current to flow from the buried electrode *A*, for example, into the earth and thence into the pipe line *D*. It will be seen, therefore, that the small 5-volt battery *F* tends to cause current flow from the pipe line *D* into the soil; whereas the motor generator set *G* tends to cause current to flow into the pipe line *D*. The motor generator set, therefore, tends to protect the pipe line *D* from corrosion by the current from the battery *F*, and if the protective tendency of the motor generator set could be made everywhere sufficiently great, it would entirely prevent corrosion of the protected pipe.

In order to determine to what extent such protective tendency existed, careful exploration was made throughout a considerable length of the pipe line *D* in order to ascertain to what points and to what extent it was discharging current into the earth under various connections of the protecting motor generator set *G*. In order to make these explorations a series of holes *H* were drilled in the ground immediately beside the pipe line *D*. These holes were drilled in pairs to the same depth as that of the pipe. One hole of each pair terminated immediately beside the pipe and the other about a foot farther away. With suitable non-polarizable electrodes the potential difference between the bottoms of the holes of each pair could be measured, and this was, of course, proportional to the surface intensity of the current discharged from the pipe surface assuming uniform soil resistance throughout, which was substantially the case. By measuring the potential difference between the bottoms of the different pairs of holes we could then plot a curve showing the intensity of the current discharged along the length of the pipe.

A series of such measurements were first made with the motor generator set connected between the buried pipe line *D* and the buried electrode *A*. The motor generator set was then connected between *D* and the buried electrode *B*, and the series of measurements on all the holes repeated, after which a similar series of measurements was made with the motor generator set connected between *D* and *C*. The results of these measurements are plotted in curves shown in Fig. 8, shown on the same sheet, both figures being drawn to the same scale. In this figure curve *D* shows the potential difference between the bottoms of the test holes when the motor generator *G* was disconnected entirely—in other words, when there was no tendency whatever to protect the pipe line *D* from corrosion. The ordinates of this curve show roughly, the relative danger of corrosion of the pipe at any point along its length, and it will be seen that the pipe is positive throughout. The motor generator set was then connected between the pipe line *D* and the buried electrode *C*, which was buried at a distance of 40 inches from the pipe line *D*.

It was found necessary in the preliminary experiments to impress about 50 volts from the motor generator set in order to get any appreciable amount of protection even in the immediate vicinity of the buried anode, and this voltage was therefore maintained throughout the test. With the 50 volts impressed between the anode *C* and the pipe line the series of potential measurements between the bottoms of the test holes gave the curve *C*. It will be seen that in the immediate vicinity of the buried anode there is a marked reversal of polarity, the pipe being strongly negative to earth for a distance approximately equal to the length of the anode.

As we proceed along the pipe, however, the negative condition of the pipe diminishes with great rapidity, and at a distance of about 4 feet from the end of the buried anode it will be seen that the pipe has become positive, and as we proceed farther away from the anode along the pipe we find that the pipe becomes more and more strongly positive to the soil until at a distance of about 20 feet from the buried anode the potential of the pipe against the earth is practically the same as it was without the motor generator connected to the anode. The remaining length of the pipe as far as explored was in practically the same condition. The motor generator set was then connected between the pipe line D to the buried anode B, which was located at a distance of



FIGS. 7 and 8.—*Diagram of arrangement of pipes for test of cathodic protection and curves showing extent of protection afforded*

80 inches from the pipe line D, or twice as far as anode C. The series of potential measurements was then repeated and the data plotted as curve B.

It will be seen here that the negative condition of the pipe *D* immediately opposite the buried electrode is less pronounced than in the case where the electrode is buried nearer the pipe, but the negative condition persists for a greater distance along the pipe line to be protected, in this case the pipe line remaining negative to earth for a distance of about 18 feet. Throughout its remaining length the pipe was positive to earth, although its positive condition was much less pronounced than in the case of the unprotected pipe. The motor generator set was next connected between the pipe line *D* and the buried anode *A*, which was located about 160 inches from the pipe line, or four times as far as the anode *C*. Potential measurements taken in the bottoms of the test holes under this condition are plotted as curve *A*. Here it will be seen that the extent of the protected zone is greatly increased, the pipe line remaining more or less negative to earth for a distance of more than 50 feet, beyond which it became positive, and consequently very little protection could be expected beyond a hundred feet or so from the buried electrode.

It appears from these tests that making a pipe system negative against a buried anode will protect the pipe only in a very small area immediately surrounding the anode. Even in this present case, where the protecting voltage was 10 times the normal potential difference between the buried pipe lines, we find the area of the protected zone to be almost insignificant, and it is very evident that if the protecting voltage were reduced, the area of the protected zone would be reduced correspondingly. In any actual case it would be impracticable to use so high a protective voltage as was used in these experiments, because of the large expense involved, both for the generator units and for the power wasted, so that the results obtained here, although wholly inadequate to afford any appreciable protection, are nevertheless better than could be expected from any practical application of this method of protection.

When, however, the rails are used as positive terminals instead of a small buried anode, the anode is in effect spread over a very large area, and consequently the radius of the protected zone would be much larger than in the case above considered. It appears, therefore, that these patented modifications involving the use of small buried anodes are without merit.

Another form of cathodic protection consists in burying near the pipes a metal which is electropositive to the pipes, such as zinc, and connecting this metallically to the pipes. This tends to protect a small area of pipe near the point of connection, but from the experiments described above it will be obvious that the radius of the protected zone will be extremely small. It has the further disadvantage that a greater number of such connections are required to protect the pipe line, and the zinc or other protecting metal rapidly wastes away. Further, there is no cheap metal which is electropositive to iron, and the expense of this method is therefore prohibitive, except perhaps in extreme cases.

All of the above modifications which employ a booster to lower the mean potential of the pipes tend to cause increased current flow in the pipes, and they also lower their potential with respect to surrounding structures, thereby increasing the danger to the latter. They are, therefore, open to the same objections as the pipe-drainage system described later in this report, besides being as a rule more complicated and more expensive to install and operate.

5. FAVORABLE LOCATION OF PIPES WITH RESPECT TO TRACKS

The location of pipe lines with respect to tracks has a very important bearing on the danger of electrolysis. In general, it may be said that the farther the pipes are from the tracks the less current they will pick up, and hence the total damage will be correspondingly reduced. A more important matter, however, is the distribution of the discharge, it being desirable as far as practicable to distribute the discharge over as large an area as possible. If the pipe in the positive area be brought near to the tracks at one point, as by crossing immediately under it, the tendency is to concentrate the discharge at that point and thereby cause rapid destruction locally. The location of the pipes is therefore more important within the positive area than outside this zone, although in both cases it is important.

In laying new pipes, or replacing old ones therefore, the pipes should be placed as far as practicable from the rails and the crossing of service pipes under the tracks should be avoided if circumstances permit. Some companies make it their regular practice in the more densely built up districts to lay mains on both sides of the street, in which case the crossing of services under tracks is rarely necessary. In many cases this is not practicable, however, but something can always be accomplished by laying the pipes as deep as possible where they pass under the tracks. The practice of putting mains immediately under the tracks tends greatly to increase damage by electrolysis and should be avoided wherever possible.

It has been contended by some investigators that it is feasible to eliminate altogether damage by electrolysis by taking precautions to keep all parts of the pipe system more than 4 or 5 feet distant from the railway tracks. This plan has been advocated rather strongly by some European engineers, notably Messrs. J. G. and R. G. Cunliffe,[4] who have concluded from extensive experiments on the resistance of ground plates that the tendency of the earth to short-circuit the pipes is so great that if a pipe line is everywhere more than 4 or 5 feet distant from the tracks it will pick up practically no current from the earth.

We are convinced, however, that this deduction is in error. In the first place, the experiments on which this conclusion was based were carried out on very small ground plates in which, obviously, the greater part of the resistance between the electrodes would be within 2 or 3 feet of the electrodes themselves, because of the relatively small cross section of the path of the current in those parts. If, however, we are dealing with very large electrodes, we find that a large part of the resistance between the electrodes is to be found at points much farther from the electrodes. Consequently, if current is being discharged from a very large electrode, the pipe line would have to be removed much farther from the vicinity in order not to pick up any current from it.

In any actual case, we may consider a railway system as constituting a large network forming a single anode discharging current into the earth, and in such a case we can not apply the conclusions that would be drawn from comparatively small anodes, such as used in the experiments above referred to. On the contrary, our own experiments have convinced us that it is wholly impracticable to so locate the pipes that they will not be in danger of picking up considerable amounts of current from the earth under conditions which in the past have usually prevailed in most cities in this country. As evidence of this we may cite the fact that quite frequently when investigating voltage conditions in various cities we have encountered localities where even at a distance of 200 yards from the nearest railway line the potential gradients in the earth were as high as several volts per mile.

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[4] J. G. and R. G. Cunliffe, "Electric traction vagabond currents," Jour. Inst. of Elec. Eng., Vol 43, p. 449.

It is very obvious that a pipe line placed in earth in which such large potential gradients exist, must of necessity pick up large amounts of current. While, therefore, the method of reducing electrolysis troubles by careful location of the pipe lines can never be more than partly successful, we are nevertheless convinced that a good deal can be accomplished in laying new lines by keeping them as far as practicable from the street railway tracks. The advantage of this, as pointed out above, is more because it tends to distribute the current discharge over a large area than because of actual reduction of current in the pipe systems, although the latter is, of course, of some consequence. The limitations of the method of pipe location are, however, very obvious. The major part of the electrolysis problem has to do with the protection of pipe systems where both the pipes and the tracks are already in place; hence this method should be regarded merely as presenting certain features, of which advantage can and should be taken in special cases, and not as a general method of electrolysis mitigation.

6. CONDUCTING COATINGS

If it were practicable to provide a continuous conducting coating for the pipes which would not corrode under the discharge of electric currents, there would be less need of trying to prevent the flow of current in the pipes. Numerous attempts have been made to utilize this principle in electrolysis mitigation. In general, the aim has been to provide on the surface of the pipe a conducting material which is noncorrodable, and which is in metallic contact with the pipe, the idea being that the current would pass from the pipe to the noncorrodable material by metallic conduction, and thence be discharged into the earth without injury. The difficulties of this method lie in the fact that all noncorrodable metals available for this purpose are too expensive for commercial application, so that attempts to use this method have necessarily been confined to nonmetallic coatings. Here, however, a difficulty is encountered, owing to the impracticability of maintaining a continuous coating by means of any nonmetallic conducting material.

In one attempt to utilize the method of conducting coatings the iron was covered by a layer of black oxide, either by subjecting it to the well-known Bower-Barff treatment or by various other means. Black oxide is a very good conductor of electricity and is noncorrodable under most soil conditions, and at first sight this method might appear promising. It has, however, two serious drawbacks which combine to make the method utterly ineffective in practice. The first is the fact that it has been impossible to to provide a coating of this kind that was entirely free from cracks or other flaws reaching through the coating to the iron below. The second difficulty is due to the fact that iron oxide is electronegative to iron, and wherever a fault develops in the coating permitting soil waters to enter and make contact with the iron, galvanic action is set up which speedily produces severe pitting in the iron. In fact, it is this phenomenon which is in large measure responsible for the unequal corrosion of iron in practice which results in pitting of the surface. The initial corrosion results in the formation of iron oxides at certain points, and these areas at once become electronegative, forcing the current to discharge elsewhere and thus aggravating the rate of deterioration of the pipes.

A patented modification of this method consists essentially in providing a coating of conducting particles such as coke, for example, embedded in a continuous nonconducting binding material, such as pitch, the theory being that the particles of coke would afford a metallic path for the current through the coating, and thus prevent corrosion of the iron. In practice it has been found that the insulating coating soon breaks down after the manner described above for paint coatings, and when this takes place the particles of coke in contact with the iron set up galvanic action, which causes rapid deterioration of the pipe. It is safe to say that conducting coatings as applied up to the present time have invariably been harmful in their effects because of this tendency to produce a greatly increased amount of self-corrosion.

7. ELECTRIC SCREENS

A method that has been used in some cases to reduce cases of local electrolysis consists in interposing between the pipes and the structure to which it is discharging current a mass of metal which is electrically connected to the pipe or other structure to be protected. The current is then carried from the pipe to the metal screen by way of the metallic path, and thence discharged into the earth, the corrosion taking place on the screen instead of on the pipe. The screen can be of heavy cast-iron plates or grids. In order to be effective the screen must be placed on the side of the pipe toward which it tends to discharge current, and if the pipe is discharging current in all directions, the screen must take the form of a larger pipe inclosing the pipe which is to be protected.

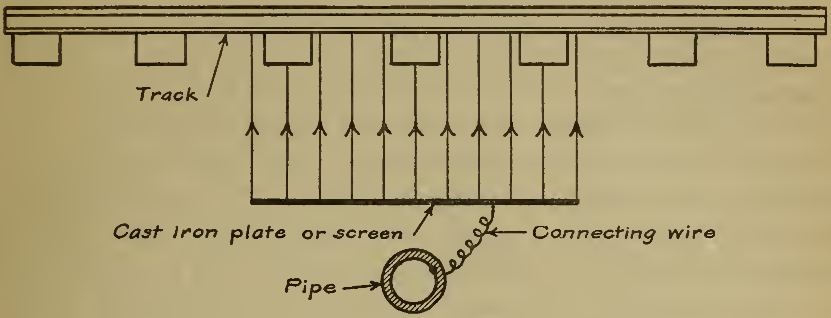

FIG. 9.—*Plane screen*

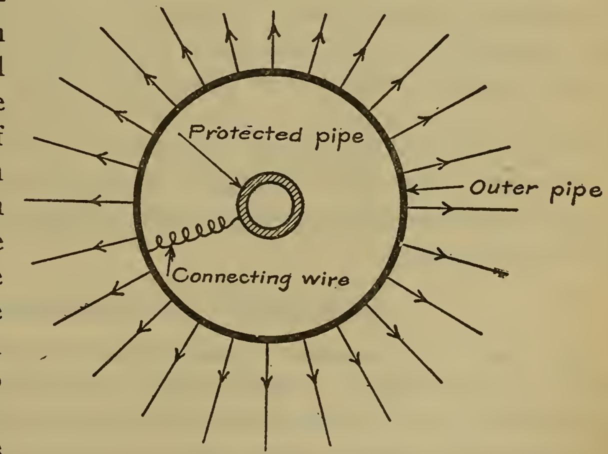

FIG. 10.—*Circular screen*

The principle of such screens is shown in Figs. 9 and 10. Fig. 9 shows diagrammatically a plain screen interposed between the pipe line and the railway track where the pipe crosses under the track. In this case the tendency would be for the pipe to discharge current upward into the track, so that a small slab of metal, such as cast iron considerably longer than the width of the track and having a width several times the diameter of the pipe interposed between pipe and tracks and connected to the pipe electrically, would take off the greater part of the current on the pipe without injury to the pipe itself; and if the iron slab were very heavy, it would in most cases last almost indefinitely. Fig. 10 shows a circular screen surrounding a pipe which tends to discharge current locally in several directions. The chief advantage of such a screen over a direct bond between the pipe and the structure to which it is discharging current is that the screen has an almost negligible tendency to increase the magnitude of the current flow in the pipes, and therefore can not induce a dangerous condition to the pipes or other structures at remote points, where they are not electrically continuous.

It is obvious that this method is not adapted for extensive use throughout the pipe system, but it may be useful in special cases for relieving severe cases of corrosion in very restricted areas, as, for example, where an important pipe line passes under or very near a street railway line or other pipe system which is strongly negative to the pipe to be protected. At best, however, it should be regarded as a temporary expedient to be resorted to only in emergency, while more adequate mitigative measures are being applied elsewhere in accordance with principles set forth in a later part of this report.

8. INSULATING JOINTS IN PIPES

(*a*) *General Discussion.*—Another method of reducing current flow in pipes which has found rather extensive application within the last few years, in some cases for the primary purpose of reducing electrolysis, but in most cases for other reasons, is that of breaking up the continuity of the pipe lines by the use of insulating or resistance joints, particularly cement joints. In ordinary wrought-iron or steel pipes with screwed or riveted joints the resistance of the joints is usually small in comparison with that of the pipes, and when such pipes are laid in localities where there is an appreciable potential gradient in the direction of the pipe current of considerable magnitude will usually be carried by the pipe. In the case of cast-iron mains the resistance of the joints is often as great as or greater than a section of the pipe, and it is not uncommon to find a lead joint which has a resistance equivalent to that of several hundred feet or even several thousand feet of pipe, and it is due largely to this high joint resistance and to some extent also to the higher specific resistance of cast iron that cast-iron mains usually carry less current under similar conditions than wrought-iron or steel mains. Experience has shown, however, that the resistance of lead joints is not sufficient to reduce the current to a safe value, and attempts have been made still further to increase the resistance of the pipes by the introduction of specially designed joints of high resistance.

Because of the wide use that is now being made of insulating joints, both for the purpose of protecting against electrolysis and for other reasons, we give below a rather full discussion of the use of such joints and the precautions that should be taken in installing them. It should be emphasized, however, that in general we regard the use of insulating joints as valuable chiefly as an auxiliary measure which may often be used to advantage to supplement measures applied to the railway tracks to reduce voltage drops therein to reasonably low values.

Following the earlier attempts to prevent electrolysis by this method, very strong claims were made for it by some of its advocates, some of them claiming that they had completely solved the problem of electrolysis mitigation by the use of insulating joints. Within a few years, however, a noticeable reaction set in. Many engineers criticized the method, and some of those who were its warmest advocates in the beginning abandoned it. It is but natural, however, that the initial attempts to apply this method should have resulted in some disappointments, and it is not safe to consider these early failures seriously in judging the value of the method when properly applied. At that time no experience had been gained in regard to the frequency with which such joints should be used, the proper location of the joints, the kind of joints best suited to certain conditions, and the complications arising from the presence of other pipe systems not so insulated.

All of these are important factors and must be carefully considered if adequate protection is to be secured.

On account of the very great number of systems, particularly gas systems, which now use cement or other insulating joints, this subject has become a very important one and requires somewhat extended discussion. We therefore give below a rather full statement of the principles underlying the design and construction of the resistance-joint systems where electrolysis mitigation is the primary consideration and also give an account of some of our own investigations that have been completed to date in regard to the use of such joints.

A number of cases have come to our attention where systems in which insulating joints have been installed for the express purpose of preventing electrolysis have, nevertheless, suffered severely from corrosion by stray currents. In every case that we have examined, however, there has been good reason for believing that the trouble was due either to the use of an insufficient number of joints, or joints of improper design, or to the fact that they were not located in such places as to be most effective in reducing danger. A very common procedure has been to insert insulating joints at infrequent intervals of from 200 to 500 feet or to insert a single insulating joint on either side of the track, and a few feet therefrom, and to assume that these insulating joints should prevent current from getting from the railway tracks into the pipes beyond the joint.

The reason why such an installation might fail to protect the pipes in many instances will be evident if we consider the conditions which exist in many places. In the course of voltage surveys in various cities we have often encountered localities where the potential difference over distances of a few hundred feet reach 5 or 6 volts or more during the average all-day load, and considerably higher values during peak load. At times potential gradients of this magnitude have been found to prevail continuously over distances of a thousand feet or more. In a case of this kind, where the difference of potential is, say, 10 volts per thousand feet, and a pipe line is located in a direction approximately parallel to the electromotive force, heavy currents will, as a rule, be picked up by the pipes, and if this is discharged into the earth, serious damage will, of course, result. If, now, we break up the continuity of the pipe by inserting insulating joints at intervals of, say, 300 feet, these joint resistances, being high compared with the resistance of the pipe, practically all of the potential drop will be concentrated at the joints and across each joint a potential drop of about 3.3 volts will occur.

Since, as usually made, the leakage path around such joints is very short, the metal parts on opposite sides of the joint being brought within an inch or less of each other, it is evident that the potential gradient across this short distance will be extremely high, and as a consequence heavy leakage currents will flow around the joints sufficient to destroy them within a comparatively short time. It is evident that in order to prevent this a sufficient number of insulating joints must be used so that the drop of potential across each joint will not be sufficient to injure the joint within a long period of years. In other words, the total resistance of the line must be so much increased by the addition of the joints that the current flowing through it under the total potential difference will be too small to do serious damage. This points to the importance of governing the number and location of the joints by the local potential conditions, a subject which is taken up in detail in a later part of this paper.

(*b*) *Tests on Insulating Joints in Service.*—In attempting to determine by actual experiment under practical conditions just how effective insulating joints may be in reducing currents in pipes, difficulties are met with owing to the complex and uncertain ramification of the pipe networks. In connection with other lines of field work we have made excavations and measured the flow of current in pipe lines provided with insulating joints at more or less frequent intervals, and by comparing these with similar measurements on lines not provided with insulating joints but otherwise similarly situated, an approximate idea has been gained as to the extent to which the currents are reduced by the joints. In making such measurements the method used was the one most commonly employed by engineers for this purpose, viz, to expose a portion of the pipes between adjacent joints and with a millivoltmeter measure the drop of potential between two points a measured distance apart. The size, type, and class of pipe being known, and the specific resistance being obtained from tables prepared for this purpose, the current in the pipe could be calculated with a sufficient degree of accuracy for work of this kind.

Wherever practicable the current measurements were made in cities where one pipe system only (either water or gas) was provided with insulating joints, and by selecting places where the pipes of the two systems lay parallel and near together for some distance it was possible to obtain points at which the two systems were subjected to somewhat similar conditions except for the insulating joints, and in this way a fairly definite idea of the effect of insulating joints could be obtained. Such readings are of course not altogether satisfactory, for there was often a difference in the material of the pipe and in some cases a difference in size also, and allowance should be made for these. There was also the uncertainty in regard to the ramifications of the network to which the lines were connected, but in general the conditions were sufficiently similar to indicate clearly the tendency of the joints.

A number of these current readings in parallel mains is shown in Table 3. In test No. 1, the measurements were taken on an 8-inch water main provided with very infrequent leadite joints, and on the same street measurements were taken on a 6-inch gas main provided with lead joints throughout. As shown in the table, the current in the former was 0.93 ampere and in the latter 1.57 amperes, showing an appreciable reduction, although the difference is small. It is important to note, however, that in this case the leadite joints were at a considerable distance apart, averaging several thousand feet, and further, they were not installed with the idea of making them insulating, so that in many cases the joints were of low resistance owing to contact between the bell and spigot ends of the pipes. In test No. 2 measurements were taken on a 12-inch main provided with a leadite joint every 12 feet and on a parallel 16-inch main with lead joints throughout. The difference here is very marked, the current in the lead joint line being over one hundred times that in the line having leadite in every joint. Similarly, in test No. 3, where also one line was provided with a leadite joint every 12 feet, the difference is more marked, the current in the case of lead joints being about a hundred and twenty times that in the pipes having leadite joints. In test No. 4 the difference is much less, but this is partly due, no doubt, to the difference in size of the pipes, as shown by the table. The chief factor, however, is the distance between the leadite joints, this being in the present instance about 300 feet.

TABLE 3

Effect of Insulating Joints on Current Flow in Parallel Mains

Test No.	Mains			Type of joint	Distribution of insulating joints in mains	Section in which drop was measured		Average potential across section	Amperes in pipe
	Kind	Class	Size			Distance to joint	Length		
			Inches				Feet	Millivolts	
1	Cast.....	D........	8	Leadite ..	Isolated....	Adjacent.	9	0.2	0.93
	Do...	A........	6	Lead.....	None......		6	.4	1.51
2	Do...	A........	12	Leadite ..	12 feet......	....do...	11½	.013	.062
	Do...	C........	16	Lead.....	None......		3	.2	7.27
3	Do...	D........	12	Leadite ..	12 feet......	....do...	10½	.013	.094
	Do...	C........	16	Lead.....	None......		8	.83	11.31
4	Do...	D........	12	Leadite ..	300 feet.....	....do...	11	.02	.138
	Do...	C........	4	Lead.....	None......		6	.3	.86
5	Wrought.	Standard.	6	No. 6 D..	Isolated....	....do...	3	.005	.037
	Cast.....	C........	6	Lead.....	None......		3½	.8	6.13
6	Wrought.	Standard.	4	No. 6 D..	Irregular...	....do...	2¼	.01	.062
	Cast.....	C........	4	Lead.....	None......		10¾	8.0	12.85
7	Wrought.	Standard.	6	No. 6 D..	Irregular...	....do...	3	.0025	.0185
	Cast.....	C........	20	Lead.....	None......		10½	1.9	28.22
8	Wrought.	Standard.	4	No. 6 D..	Irregular...	....do...	2½	.01	.056
	Cast.....	C........	4	Lead.....	None......		7	.15	.371
9	Wrought.	Standard.	6	No. 6 D..	Irregular...	....do...	1⅓	.0025	.042
	Cast.....	C........	6	Lead.....	None......		11⅙	.02	.048
10	Wrought.	Standard.	8	No. 6 D..	Irregular...	....do...	2½	.0025	.031
	Cast.....	C........	6	Lead.....	None......		11¾	2.4	5.47
11	Wrought.	Standard.	3	No. 39 D.	20 feet......	....do...	22	.005	.0024
	Cast.....	C........	6	Lead.....	None......		10½	2.0	5.11
12	Wrought.	Standard.	3	No. 6 D..	Irregular...	1000 feet..	10	1.2	1.26
	Cast.....	C........	10	Lead.....	None......		10	.3	1.62
13	Wrought.	Standard.	3	No. 6 D..	Irregular...	1300 feet..	4	.01	.026
	Cast.....	C........	12	Lead.....	None......		10	.5	3.50
	....do...	C........	12	.....do...	.....do.....		10	.2	1.40
14	Wrought.	Standard.	3	No. 6 D..	Irregular...	500 feet...	10	.015	.016
	Cast.....	C........	10	Lead.....	None......		10	5.0	27.0

TABLE 4

Small Currents Flowing in Mains Protected by Insulating Joints

Mains			Joints		Distribution of insulating joints in mains	Section in which drop was measured		Average potential across section	Amperes in pipe
Kind	Class	Size	Type	Age		Distance from insulating joints	Length		
		Inches		Years			Feet	Millivolts	
Cast	D	12	Leadite	3	12 feet	Adjacent	12	0.013	0.082
Do	D	12	do	3	do	do	10½	.013	.094
Do	D	12	do	3	do	do	11	.013	.090
Do	D	12	do	2	do	do	8	.01	.095
Do	D	12	do	2	do	do	11	.041	.283
Do	D	12	do	3	do	do	11	.01	.069
Do	D	12	do	4	Isolated	do	10¼	.02	.148
Do	D	12	do	4	300 feet	do	11	.02	.138
Do	D	12	Wood	3	Isolated	do	6	.01	.127
Do	D	12	do	3	do	100 feet	6	.03	.38
Wrought	Standard	4	No. 6 D	4	20 feet	Adjacent	8	.0025	.0044
Do	do	6	do	4	Isolated	do	3	.005	.037
Do	do	4	do	4	Irregular	do	225	.01	.00063
Do	od	6	do	4	do	do	3	.0025	.0185
Do	do	4	do	4	do	do	2½	.01	.056
Do	do	6	do	4	do	do	1⅓	.0025	.043
Do	do	8	do	4	do	do	2½	.0025	.031
Do	do	3	No. 39 D	4	20 feet	do	2⅛	.005	.024
Do	do	3	No. 6 D	2	Irregular	1000 feet	10	.0025	.0026
Do	do	3	do	2	do	1300 feet	4	— .01	— .0263
Do	do	4	do	2	do	200 feet	10	.015	.0211
Do	do	4	do	2	do	Adjacent	3	.025	.1175
Do	do	4	do	2	do	1200 feet	6	.02	.047
Do	do	4	do	2	do	600 feet	6	.01	.0235
Do	do	4	do	2	do	Adjacent	4	.0025	.0088
Cast	C	6	do	2	do	do	3½	.01	.0765
Wrought	Standard	3	do	2	do	500 feet	10	.015	.0157
Cast	C	8	do	2	do	2500 feet	6	.2	1.30
Wrought	Standard	4	do	2	do	750 feet	6	.1	.235
Cast	C	6	Cement	10	12 feet	Adjacent	11	.0025	.0061
Do	C	6	do	10	do	do	11	.015	.0365
Do	C	6	do	10	do	do	11	.05	.122

Tests No. 5 to 11, inclusive, were made on wrought-iron gas mains provided with Dresser couplings at irregular intervals and on parallel cast-iron water mains provided with lead joints. In comparing these figures it should be borne in mind that cast iron has a much higher resistance than wrought iron, and further that the lead joints themselves introduce considerable resistance into the circuit, so that the real effect of the Dresser joints is much greater than the figures would indicate. While considerable variation exists in the ratios of current in parallel mains in the different tests of this series, they show without exception considerable reduction in current due to the insulating joints. Taking the average of the series we find that the current in the lines having lead joints is about thirty-six times that in the lines having insulating joints.

TABLE 5

Current Mains in Mains When Joints are Infrequent

Mains			Joints		Distribution of insulating joints in mains	Section in which drop was measured		Average potential across section	Amperes in pipe
Kind	Class	Size	Type	Age		Distance from insulating joints	Length		
		Inches		Years			Feet	Millivolts	
Cast.....	D........	8	Leadite	4	Isolated..	Adjacent.	9	0.2	0.926
Do....	C........	30	...do...	3	.....d....	.....do....	11	.2	5.45
Wrought.	Standard.	6	No. 6 D	4	Irregular	1000 feet..	3	.04	.296
Do....	...do......	6	...do...	4	.....do...	600 feet...	2¾	.25	2.02
Do....	...do......	4	...do...	4	.....do...	300 feet...	2	.11	.775
Do....	...do......	4	...do...	2	.....do...	200 feet...	19	1.0	.742
Do....	Casing...	5⅝	...do...	2	.....do...	2500 feet..	6	.05	.78
Do....	Standard.	6	...do...	2	.....do...	1200 feet..	2	.4	4.44
Do....	...do......	8	...do...	2	.....do...	300 feet...	3	.6	6.18
Do....	...do......	4	...do...	2	.....do...	1200 feet..	2½	.4	2.25

In all of these cases, except in test No. 11, the insulating joints were irregularly spaced, the distance between joints in various parts of the system varying from three hundred to several thousand feet. This fact being considered, the relatively low values of current in the lines provided with insulating joints is quite remarkable. In the last two tests shown in Table 3 (Nos. 13 and 14) the ratios of current in the lead jointed lines to that in the lines with insulating joints are, respectively, 134 and 168, but in these tests considerable allowance must be made for the relatively large size of the cast-iron mains as shown by the table.

In Table 4 is shown a series of current measurements on lines having insulating joints under conditions where, in most cases, it was not possible to obtain similar readings on lines not so insulated, and they are presented here merely to show that in general these currents have been found to be very low. These figures may be regarded as typical of what may be expected under ordinary conditions where a considerable number of insulating joints are used. That the current in these systems was not invariably small, however, is shown in Table 5, which gives a number of tests showing current of considerable magnitude flowing in the pipes. It is to be noted, however, that in all such cases the insulating joints were widely separated, as shown by the column giving the distance from the nearest insulating joint to the point at which the measurements were taken. The distance between joints being at least double these values, they range, therefore, from four hundred to several thousand feet. These figures emphasize the fact pointed out above that if the joints are placed too far apart in places where potential gradients in the earth are high, enough current may continue to flow through the pipes to cause serious damage.

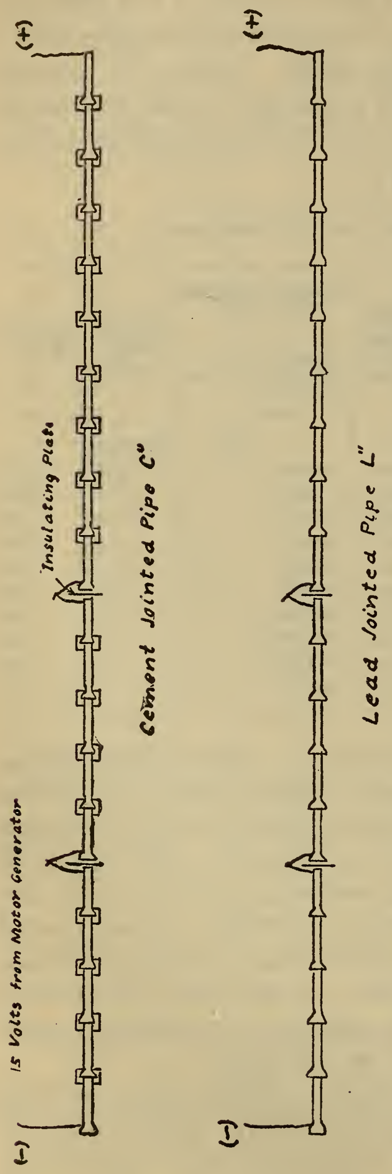

FIG. 11.—*Arrangement of cast-iron pipe lines for determining the relative resistance of cement and lead joints*

In all of the cases above referred to the resistance joints were either spaced at considerable distances apart or were not carefully enough made to insure a high resistance; they do not therefore show what may be accomplished by the use of insulating joints when installed at very frequent intervals and when proper care is taken to eliminate defects in the joints. In order to secure further and more exact data on this point two experimental lines of 4-inch cast-iron pipe were laid at the Bureau of Standards under conditions which insured identical conditions except for the joints. The lines were laid parallel, 100 feet long and 40 feet apart, one line being provided with ordinary lead joints and the other with carefully made cement joints.

The arrangements of these pipes is shown in Fig. 11. At the center of each line the pipes were separated by a large insulating plate and to the ends of the pipes adjoining this plate insulated leads were attached, and these were brought to the surface and short-circuited, an ammeter being inserted in these leads when it was desired to measure the current in the pipes. A difference of potential of 15 volts was impressed on the pipes and measurements of the current flowing in the pipes were made. The results are given in Table 6, and are a most striking illustration of the effect of carefully installed insulating joints in keeping the currents off the pipes. It will be seen that the current flowing in the line provided with cement joints was, when last measured, less than one twenty-two thousandth part of that flowing in the line having lead joints, and is decreasing. This current is so small as to be entirely negligible, in so far as electrolysis effects are concerned.

TABLE 6

Current in Parallel Cement and Lead Joints

Date	Voltage	Current		Ratio, lead to cement
		Cement	Lead	
May 8, 1911	15	0.0032	29.1	9 100
Nov. 2, 1911	15	.0011	24.2	22 000

It is very important to note that in the systems mentioned above not only have the currents in the pipes been reduced to relatively small values by means of insulating joints, but the systems thus protected have been singularly free from electrolysis troubles since the joints were installed. Although they have been in service for periods varying from 2 to 10 years or longer no serious cases of trouble have arisen, although in some instances other systems laid in the same streets and not so protected have suffered considerable damage from electrolysis. As an example, we may cite the experience of the Cambridge Gas Co., of Cambridge, Mass. This company uses cement joints exclusively in their gas mains and they have had but little trouble from electrolysis, while the water pipes occupying the same region and not so protected are reported to have suffered severely for years.

(*c*) *Resistance of Various Types of Insulating Joints in Practice.*—While the foregoing shows that insulating or resistance joints when properly installed and used in sufficient number will very greatly reduce the flow of current in pipes, there are certain features in connection with such installations, which, if not guarded against, may give rise to considerable trouble. In the first place, joints designed and installed as insulating joints may or may not be insulating when completed, and this is especially apt to be true after the joints have been in service for a considerable length of time. A little carelessness in making the joint may permit the two ends of the pipe to make metallic contact, in which case, of course, the joint becomes worthless as a protection against electrolysis. This is particularly apt to occur in making joints where cement or leadite is substituted for lead, but it can easily be guarded against with a little care. But even when every care is exercised in making the joints, they will often show surprisingly low resistances after having been in service for a considerable time.

Table 7 shows the resistances of a number of so-called insulating joints in actual service selected at random, and these are typical of what may be expected. In measuring these resistances, a joint and a portion of the pipe were uncovered and the drop across the joint compared with that across a measured length of pipe either by means of a voltmeter or with a slide wire bridge. The size, weight, and material of the pipe being known, the resistance of both pipe and joint in ohms could also be calculated with a fair degree of accuracy. It is to be noted that a number of joints show an extremely low resistance, comparable with that of an ordinary lead joint, thereby indicating metallic contact of the pipes. This is particularly true of some of the leadite joints. It is important to note that the leadite joints were made without any attempt to make them insulating and this may be largely responsible for the large proportion of very low resistance joints.

TABLE 7

Resistance of Joints in Service

Mains			Joints		Average potential across joint	Resistance of joints	
Kind	Class	Size	Type	Age		Ohms	Length of pipe with same resistance
		Inches		Years	Millivolts		Feet
Cast	D	8	Leadite	4	0.8	0.00133	36
Do	D	8	do	4	20.0	.033	897
Do	D	12	do	3	8.0	.123	7230
Da	D	12	do	3	.02	.0003	18
Do	D	12	do	3	.3	.004	235
Do	D	12	do	3	1.0	.014	824
Do	D	12	do	3	5.0	.03	1760
Do	D	12	do	3	5.0	.03	1760
Do	D	12	do	2	.15	.002	118
Do	D	12	do	2	4.0	.018	1060
Do	D	12	do	2	11.0	.051	3000
Do	C	30	do	3	60.0	.015	3350
Do	C	30	do	3	5.0	.0012	269
Do	D	12	do	3	3.0	.0052	306
Do	D	12	do	3	3.0	.0052	306
Do	D	12	do	3	.6	.0113	665
Do	D	12	do	3	.12	.226	13 300
Do	D	12	do	4	40.0	.357	21 000
Do	D	12	do	4	30.0	.268	15 700
Do	D	12	do	4	40.0	.357	21 000
Do	D	12	do	4	3.0	.028	1650
Do	D	12	do	4	6.0	.057	3350
Do	D	12	18-foot wood stave	3	4000.0	40.0	2 350 000
Wrought	Standard	4	No. 6 D	4	57.0	2.64	155 000
DO	do	6	do	4	60.0	.36	37 600
Do	do	4	do	4	1300.0	4.96	292 000
Do	do	6	do	4	400.0	4.65	480 000
Do	do	4	do	4	100.0	.425	25 000
Do	do	6	do	4	800.0	5.35	560 000
Do	do	8	do	4	750.0	9.0	1 400 000
Do	do	4	do	2	400.0	10.65	626 000
Do	do	4	do	2	200.0	9.5	558 000
Cast	C	6	do	2	80.0	.286	60 800
Do	C	6	Cement	10	0.01	.002	42

Perhaps the most surprising feature of Table 7 is the low resistance shown by the Dresser couplings which had been in service for a number of years. Although these joints are provided with rubber gaskets and doubtless had a very high resistance when new, the resistances have now fallen to a few ohms. A joint having a resistance of this magnitude, however, is practically as good as one of much higher resistance, since only currents of negligible value can flow through such a resistance under the differences of potential that would commonly prevail across the joint in practice. In the case of the joints having a resistance of a few hundredths of an ohm or lower, currents of considerable magnitude may be found, and these can not be regarded as satisfactory resistance joints. With reasonable care in the making, however, all joints whether made of cement or wood or some special joint provided with rubber or other insulating gasket will have ample resistance, and if properly located and used in a proper manner any of these joints should prove effective.

Leadite joints when new also have ample resistance, comparing favorably with cement joints in this respect, but their resistance appears to decrease rapidly with age. This is very strikingly shown in Table 8, which shows the variation of the resistance of some leadite joints with time. A pipe line about 100 feet long was laid with leadite joints, care being taken to make all joints free from metallic contact between the ends of the pipe. At the center of the line the pipes were separated and an insulating plate inserted, and the two ends of the pipe on either side of the insulating plate were provided with insulated leads, in which an ammeter could be inserted for the purpose of measuring from time to time the current flowing in the pipes. A difference of potential of 15 volts was impressed on this line continuously for several months; this was sufficient to give a drop of potential of about 0.8 volt on each joint.

TABLE 8

Showing Variation of Resistance of Leadite Joints with Time

	July 7, 1911	July 14, 1911	July 21, 1911	July 28, 1911	Aug. 11, 1911	Aug. 25, 1911	Sept. 8, 1911	Sept. 19, 1911	Feb. 19, 1915
Current	0.0069	0.0076	0.046	0.268	0.064	0.360	1.24	1.88	132.0
Resistance	2,174	1,990	326	56	23	41	12	8 ohms	0.113

The readings show that the current was very small when the pipe was first laid, but increased rapidly with time, and after being laid 4 months the resistances had decreased to about one two-thousandths of their initial value and were still decreasing.

At the end of that time the current was discontinued and the pipes were allowed to stand in earth for about 14 months, when the resistance of the line was again measured. It was then found that the resistance of the entire line had fallen to 0.25 ohm, and after about 4 years the resistance was only 0.113 ohm, or less than one nineteen thousandths part of its value at the beginning. This resistance is still high enough to have an appreciable value in reducing current flow in the pipe, the resistance of the joints being still nearly twenty times that of the pipes, but the results indicate that leadite joints can not be depended upon to remain permanently insulating, and their permanent value as a preventive of electrolysis is at least questionable. At first it was supposed that the apparent decrease in the resistance of the joints might be due to increased leakage around the joints, but measurements made of some of the joints when uncovered show that the resistance of the joint itself has decreased. It was found that the leadite contains a large amount of sulphur, and when placed in wet soil this gradually oxidizes forming sulphuric acid which appears to be chiefly responsible for the steady falling off of the resistance of the joints.

(*d*) *Number of Insulating Joints Required.*—A condition already referred to that is likely to cause trouble is a too infrequent use of insulating joints, and this condition is probably responsible for a good deal of the disfavor into which this method has fallen with some people. Obviously, if the joints are placed far apart, the long stretch of intervening pipe may pick up considerable current, and since most of this current must flow out of the pipe as it approaches the insulating joint, serious electrolysis may occur on the positive side of the joint. The more frequently the joints are placed the less the danger from this source. It is of course impossible to lay down any very definite rules in regard to the frequency with which such joints should be used, since that must be determined in each case by local conditions. In general, however, it may be said that the resistance joints should not be confined to the positive area as some have supposed, but should be distributed throughout the negative and neutral areas also. All lines which run near by, or cross under street railway tracks, are generally most in need of resistance joints.

In many cases where there is good reason for believing that the drop of potential is fairly uniformly distributed throughout the entire region in which the insulating joints are to be placed, it is sufficient simply to determine the total difference of potential between the ends of the line affected and use this value in determining the number of insulating joints that are needed in order that the drop of potential across each joint shall not exceed a predetermined value. It usually happens, however, that the potential gradient may vary greatly in different portions of the line and if the joints were uniformly spaced in such cases, the joints would either be more frequent than necessary in some places, or too few in others, and the condition of maximum of protection at a minimum cost would not be realized. This condition is very likely to occur where a pipe line runs at right angles to railway lines, in which case the potential gradient along the pipe will often be many times greater at points within a short distance on either side of the track than at more remote places. Other conditions, such as the presence of other pipe systems, may also disturb the uniformity of the potential drop.

In some instances, as in laying new lines where some cheap type of joint is being used, it may often be less expensive to allow a liberal factor of safety and install enough joints to be safe under any conditions that may arise; but in other cases, as, for instance, where insulating joints are to be inserted in large and important mains already laid, where the cost of each joint is an important matter and where interruption of the service is of serious moment, it is important that no unnecessary joints be used, and that these be so placed that they will be most effective in reducing current flow in the pipes, and so that there will be no danger of developing a high enough difference of potential across the joint to cause trouble. For this reason, before attempting to install a series of insulating joints for the purpose of preventing electrolysis in cases where it is important for economic or other reasons to use as few joints as possible, it is important, first, to make a careful potential survey of the district to be affected and determine the magnitude of the potential gradients in a direction parallel to the pipe lines. This will enable one to determine in advance the approximate number of joints that will be necessary and also the proper location of the joints, so that the drop of potential across any joint may not exceed a certain amount.

If a new line is to be laid, it is safe to assume that the average potential gradient after the pipe has been laid will not differ greatly from that which prevails beforehand, provided the joints are used at proper intervals; but the distribution of this potential gradient will be greatly altered, practically all of the fall of potential occurring at the joints. The average drop of potential across joints in any given portion of the line will be approximately equal to the total drop divided by the number of joints. When insulating joints are to be placed in old lines it is well to bear in mind that the insertion of the joints in the pipe will, in general, increase the potential gradient along the pipe due to reduction of current flow in the pipes. This increase may reach as much as 100 per cent or more, and allowance should be made for this.

In actually measuring the potential gradients in the earth special precautions must be taken if trustworthy results are to be obtained. The best procedure to be followed in work of this sort is discussed in detail in Technologic Paper No. 28 of the Bureau of Standards, entitled "Methods of making electrolysis surveys."

After a series of joints are installed the only method of determining experimentally whether or not a sufficient number of joints has been installed is by measuring the drop of potential across each joint and by measuring current flow in the pipes. If the joints are too few in number in any locality, there will be too high a voltage across the joints, and the consequent heavy leakage current may injure the pipe on the positive side of the joint.

As to the voltage that can be safely permitted, that is a matter which depends on a variety of conditions, such as the nature of the soil, kind of joint used, etc., and can only be roughly indicated here. Careful observation of joints under average conditions for a considerable period, together with experiments to be described later, indicate that in cast-iron mains a drop across the joint of from 0.1 to 0.4 volt can usually be regarded as safe, while in wrought-iron pipes a voltage not exceeding about one-third of these values should be allowed. The lower limit applies to pipes located in low, wet places and to joints having a short leakage path between the sections of the pipe, and the upper limit to pipes in comparatively dry soils and to joints having a long leakage path. This matter of the length of the leakage path around the joint is an important one and is treated later in discussing the relative value of different kinds of joints. If the joints used have not a very high resistance, as when leadite is used, for instance, considerable current may flow through the joints without making a dangerous drop across the joint, and the currents thus collected in a large number of branch lines may ultimately be carried to a few lines in a remote quarter and there give rise to serious damage. In order to guard against this, current measurements in the pipes should also be made. If in any line a considerable current is found to be flowing, or if the voltage across the joints exceeds considerably the limits mentioned above, additional joints should be installed, or measures should be taken to reduce potential drops in the railway return systems. The latter course should be followed where practicable.

One of the problems encountered in attempting to protect a pipe system by the use of resistance joints is the effect of other pipe systems in the same territory not so protected. Gas and water systems, for instance, are often brought into metallic contact with each other in many places, and this greatly increases the difficulty of protecting either system alone by the use of resistance joints. This difficulty could be largely avoided by inserting an insulating joint in the service pipe inside of the buildings in which metallic connections with the other system is made. This would usually be expensive, however, and there are other complications which are not so easily dealt with; where an uninsulated pipe system occupies the same territory with an insulated system, isolated cases of electrolysis are likely to occur.

When a line having insulated joints must be connected to another line not so insulated trouble may be experienced, due to the tendency to develop high potential drops across the joints in such places, particularly if the insulated pipe line is at a potential considerably different from that of the earth, either positive or negative. This condition is especially likely to occur if the uninsulated main is connected to negative return feeders, and those joints near which the negative feeders are attached, are often subjected to unavoidable differences of potential that may be sufficient to destroy the joint in a short time. For this reason the use of insulating joints and negative return feeders in the same system should be avoided.

The difference of potential that can safely be permitted across a joint presents a problem of great importance and one to which comparatively little study has been given. Some of the factors governing this are mentioned above and one of the most important of these is the type of joint used. It is well recognized that the actual damage due to the discharge of current from a pipe depends not so much on the total quantity of electricity discharged but mainly on the distribution of the discharge. If the current leaves the pipe uniformly over a large surface, a much longer period must elapse before serious damage will result than if the intensity of current discharge is much greater at some points than others, so that conditions which tend to prevent concentration of discharge will correspondingly reduce the danger. As already shown, even pipes provided with insulating joints will carry some current, and especially if the joints are not very frequent; and since with high resistance joints most of this current must leave the pipes at every joint, it becomes important to determine as accurately as possible what the distribution of this discharge may be and to find how this distribution may be made most nearly uniform.

(*e*) *Effect of Form of Joint on Distribution of Leakage.*—To determine the effect of the form of the insulating joint on the distribution of current around the joint, three perfectly insulating joints were made of 4-inch cast-iron pipe, one a bell and spigot joint with a layer of paraffin separating the pipe sections, the second a butt joint with one-half inch of paraffined wood separating the pipes, and the third a similar butt joint with 5 inches of paraffined wood between the pipes.

The pipes in succession were placed coaxially in a cylindrical tank of water 23 inches in diameter and 32 inches in depth with the joint near the center of the tank. The arrangement of the apparatus is shown in Fig. 12. The bottom of the tank was covered with a layer of paraffin and the end of the pipe rested on a glass plate. Rubber-covered leads attached to the pipes 14 inches from the joints permitted the impressing of any desired voltage on the joints.

An L-shaped, two-conductor rubber insulated cable was lowered into the water, the plane of the L being kept radial to the pipe and the end of the L bent upward so that the line joining the exposed ends of the wires at the terminus of the L was normal to the surface of the pipe. Since the specific resistance of the water was substantially uniform throughout, the potential gradient at any point was proportional to the intensity of the current at that point; hence by measuring the difference of potential between the two exposed ends of the wires when placed as close as practicable to the surface of the pipe (about 0.04 inch), a measure of the current density was obtained. The potential gradients thus obtained at any point divided by the specific resistance of the water gave the intensity of current at that point, and by raising or lowering the L the intensity of current discharge at any desired

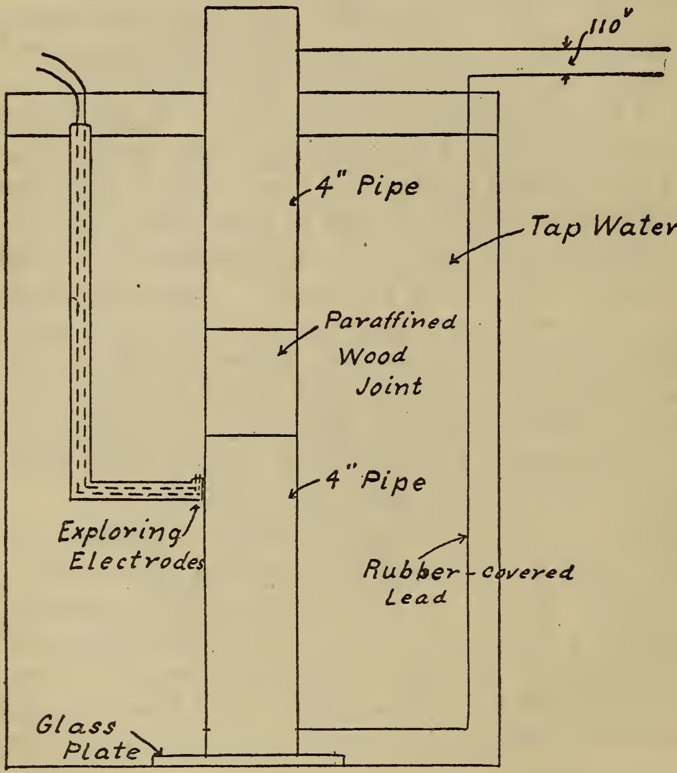

Fig. 12.—*Apparatus for determining the effect of the form of insulating joint on current distribution*

point could be found. The specific resistance of the water used was 5620 ohms per centimeter cube which is about the mean of that of a large number of samples of earth taken from a number of cities. It was necessary to impress rather high voltages across the joint and use a voltmeter of high-current sensitivity in order that the pressure readings would not be seriously affected by polarization at the terminals. From 20 to about 100 volts were used, according to the type of joint under test.

The results of the tests are very strikingly shown in the curves of Fig. 13, in which the intensity of current discharge is plotted as a function of the distance along the pipe for some distance on each side of the joint. In each case the axis of the pipe is taken as the zero axis of current and positive values represent flow of current away from the pipe, while negative values represent current returning to the pipe. For convenience in making comparisons all the readings are reduced to values corresponding to a difference of potential of 20 volts across the joint. The curves indicate that the form of the joint has a most decided effect on the distribution of current discharge. The bell and spigot type shows a very high density of current just under the edge of the bell, indicating a very high rate of corrosion at that point. The butt joint, shown at the bottom, having a length of one-half inch, shows a much better distribution of current, the maximum intensity being about one-third that in the case of the bell and spigot joint. With the joint 5 inches long, still further reduction in the height of the peak is shown, the maximum intensity of discharge being only 15 per cent of that of the bell and spigot type.

It is also very interesting to note that the total flow of current about the joint does not differ greatly in the three cases, the resistances of the leakage path being 68, 72, and 87 ohms in the bell and spigot, half-inch and 5-inch joints, respectively. Particularly significant is the comparison of the two butt joints in this respect. Although one is ten times as long as the other the resistance of the leakage path is increased only about 20 per cent. This shows the unwisdom of attempting to reduce the current flow in a pipe line merely by increasing the length of a few joints. The short joints are, as a rule, much cheaper and easier to install and they can therefore be installed much more frequently for the same total cost.

As a rule, therefore, it would appear preferable in installing a line of insulating joints to use a large number of short joints rather than a few long ones, as in this way the current in the pipes can

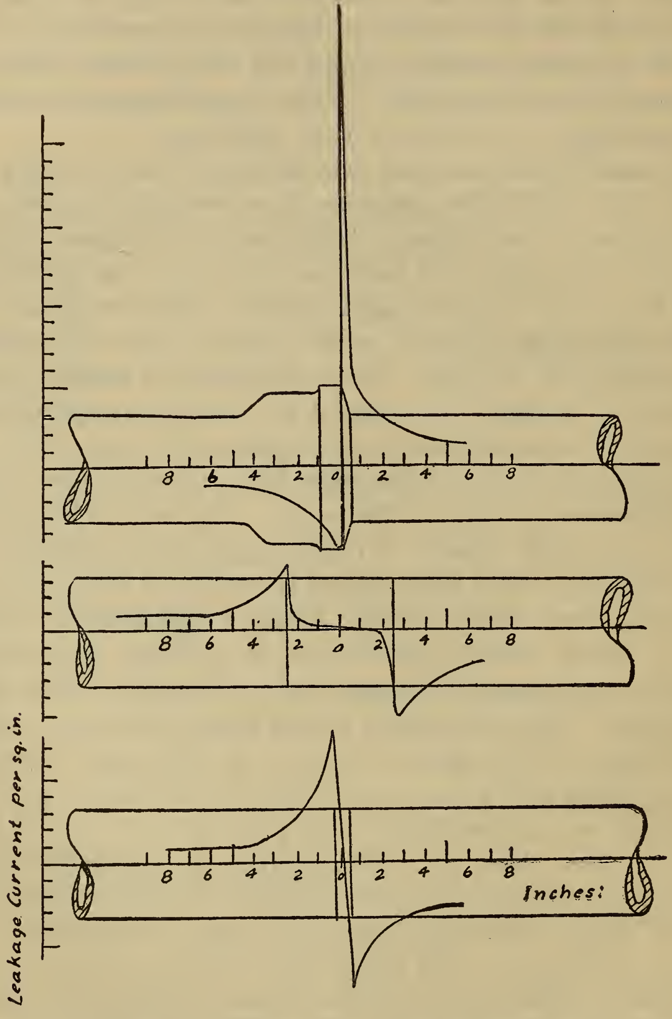

FIG. 13.—*Curves showing intensity of current discharge near insulating joints*

be kept at a much lower volume, and the relatively large number of joints will usually be sufficient to prevent any serious potential drop across the joint. In some cases, however, as where the insulating joints are discontinued, or where for any reason it is necessary to use but a few joints or to put them in places where high potential differences are unavoidable, the above tests show that the long joint is much to be preferred, because of its effect in preventing great concentration of current discharge near the edge of the joint.

Owing to the possibility that polarization effects or contact resistance between soil and pipe might seriously affect the distribution of current flow, the following experiment was carried out with a view of checking the accuracy of the deductions made from the current distribution curves of Fig. 13. For this purpose an apparatus was made up like that shown in Fig. 14. This consisted of an insulating joint *A*, made of paraffined wood, on one side of which was a short section of ordinary wrought-iron pipe *B*, and on the other side was a series of thin circular disks *C*, placed as shown in the figure. These disks were all electrically connected together, so that they were at the same potential. The object was to bury the joint in earth and impress on it a moderate potential difference with the thin circular disk on the positive side and determine the relative amount of corrosion on the different disks as a function of their distance from the insulating joints in order to see how this compared with the potential distribution curve around the joint as shown in Fig. 13. Before assembling, the individual disks were carefully cleaned and weighed. The joint was then buried in the earth and a potential difference of 15 volts impressed on it for a period of several months with the cir-

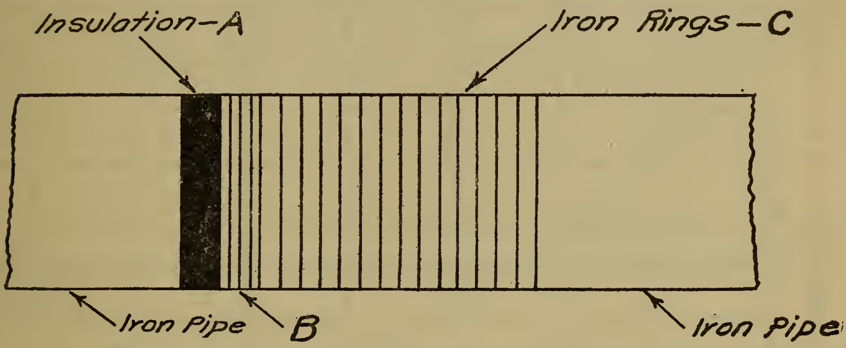

FIG. 14.—*Insulating joint for determining distribution of corrosion in earth*

cular disks on the positive side; it was then removed, the disks taken apart, carefully cleaned and weighed, as before, and the loss determined.

The result of the test is shown in Fig. 15, in which the curve represents the loss in weight of the disks as a function of the distance from the insulating joint. By comparing the shape of this curve with the current distribution curves of Fig. 13 it will be seen that they have substantially the same form, which shows that the method used in determining the curves in Fig. 13 gives a current distribution which is substantially the same as that which actually occurred in the case of the insulating joint buried in soil.

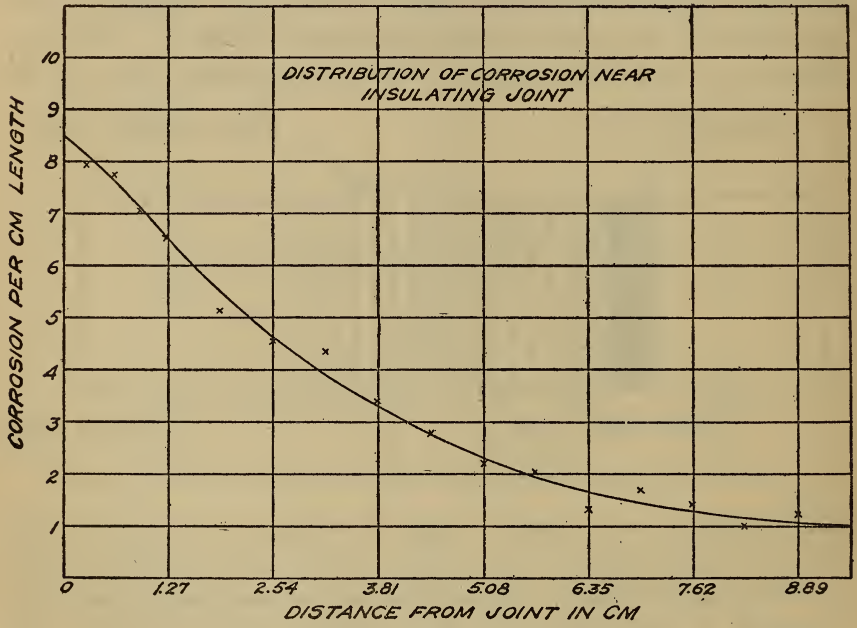

FIG. 15.—*Distribution of corrosion near insulating joint*

(*f*) *Limiting Safe Potential Drops on Insulating Joints.*—The above results furnish also a basis upon which can be made a roughly approximate determination of the voltage drop which may be permitted across a joint of the type tested. It can be shown that the rate at which corrosion will penetrate the iron is given by the formula $L=\frac{C}{D}\times\frac{P}{S}$, where L is the rate at which the corrosion penetrates the iron expressed in centimeters per year, C is the electrochemical equivalent of iron, D its density, P the average potential gradient in volts per centimeter normal to the pipe at the point considered, and S is the specific resistance of the soil in ohms per centimeter cube. The assumption is here made that the coefficient of corrosion is 100 per cent. For cast iron the value of $\frac{C}{D}$ is about 1280, and the equation becomes

$$L = 1280 \cdot \frac{P}{S}$$

Assuming 5600 ohms per centimeter cube as the average specific resistance of the soil and a drop of potential of 0.4 volt across the joint and determining from the curves in Fig. 13 the maximum current intensity reduced to this voltage, we get as the maximum rate of penetration of the corrosion in inches per year:

	Inches per year
Bell and spigot joint	0.034
One-half inch wood joint	.009
Five-inch wood joint	.004

The time required for the corrosion to penetrate clear through a pipe one-half inch thick containing these joints is therefore as follows:

	Years
Bell and spigot	14.7
One-half inch wood	53.4
Five-inch wood	121

The permissible drop across a joint in one-half inch cast-iron pipe for a life of 40 years is as follows:

	Volts
Bell and spigot joint	0.147
One-half inch wood	.53
Five-inch wood	1.22

In considering these figures it is well to remember that the corrosion here indicated is that due to electrolysis and is in addition to the self-corrosion that may also occur. It should be added that we have found the specific resistance of soils to be in some cases as low as one-tenth of the value used in these calculations, so that under practical conditions the rate of corrosion may be several times that computed above. Further, the effect of surface resistance due to paints, etc., and the effects of polarization under low voltages are not here considered, so that considerable variations from the calculated values may be expected. These calculations are of value only in that they indicate that a drop of potential across a short joint can hardly be considered safe if it exceeds a few tenths of a volt even under the best conditions, and that much can be gained by the use of a long leakage path where the voltage at each joint is necessarily high. This problem is an important one and much additional work remains to be done in this direction.

(*g*) *Types of Insulating Joints Available.*—It is well to call attention at this point to some of the various types of insulating joints that are now in use. These may be divided into four classes, viz:

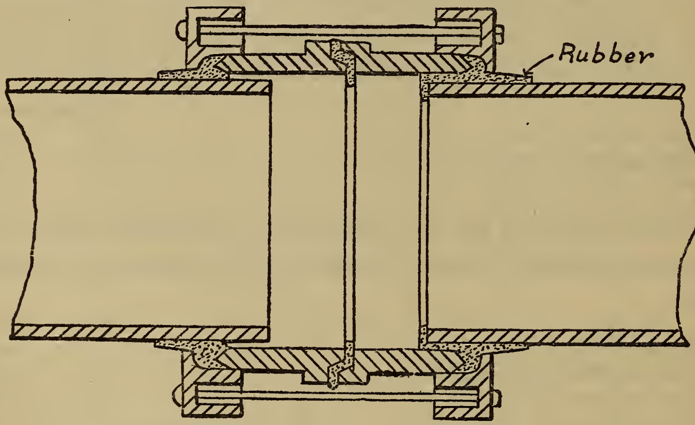

FIG. 16.—*Dresser coupling*

(1) Clamped joints, using a rubber gasket or other insulating material to make a tight joint and provide the insulating section; (2) wooden joints, including wood-stave pipe sections; (3) cement joints, of which there are various types; and (4) leadite joints.

The first of these, exemplified by the well-known Dresser coupling, is quite extensively used for the purpose of securing gas-tight joints, and some types of these are designed also to give insulating joints. When properly designed and installed, it gives a very high-resistance joint, and has been very effectively used in a number of instances for the purpose of reducing the flow of current in the pipes. The construction of one form of Dresser coupling, known as the divided center ring insulating coupling, is shown in Fig. 16. This makes a very satisfactory insulating joint for most purposes, although it may, under bad voltage conditions, be liable to injury because of the relatively short leakage path, the importance of which has already been discussed. Under most circumstances, where the local potential gradients are not too high, this should cause no trouble. Some trouble has been reported where these couplings have been used on artificial gas mains, owing to the deleterious effect of the gas on the rubber gaskets. They do not appear to be affected by natural gas, however, and in such mains they appear to show a satisfactory life.

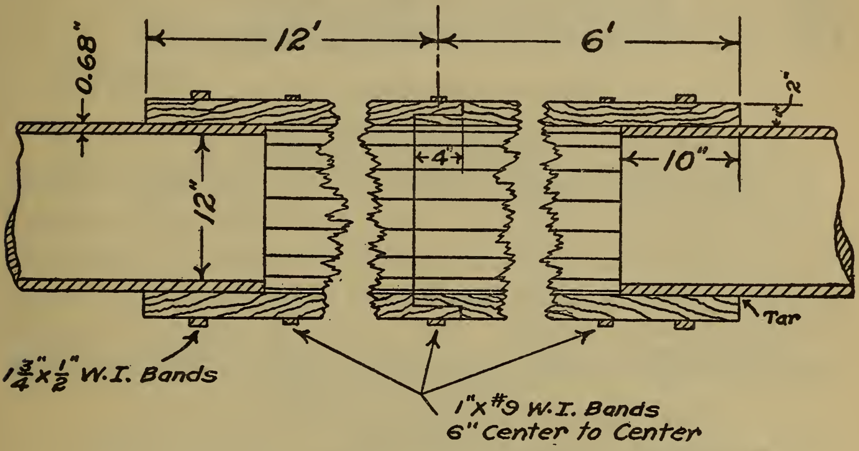

FIG. 17.—*Wood stave joint used by the Pennsylvania Water Co.*

Of the wooden joints, numerous modifications are in use. One type used by the Pennsylvania Water Co. is shown in Fig. 17, which is self-explanatory. This joint has a high electrical resistance and is particularly adapted for use in places where only one or at most a few joints are installed and the drop of potential across the joint is likely to be high. The great length of the joint is very effective in causing any leakage current around the joint to distribute itself over a considerable length of adjoining pipe, as pointed out above, and thus prevents concentration of electrolysis at the edge of the joint.

Another type of wood-stave joint is shown in Fig. 18. The spiral steel band used in this construction would have the effect of materially shortening the leakage path, and while it would have ample resistance to serve as an insulating joint under most circumstances, it could not safely withstand as high a drop of potential across the joint as the one previously described.

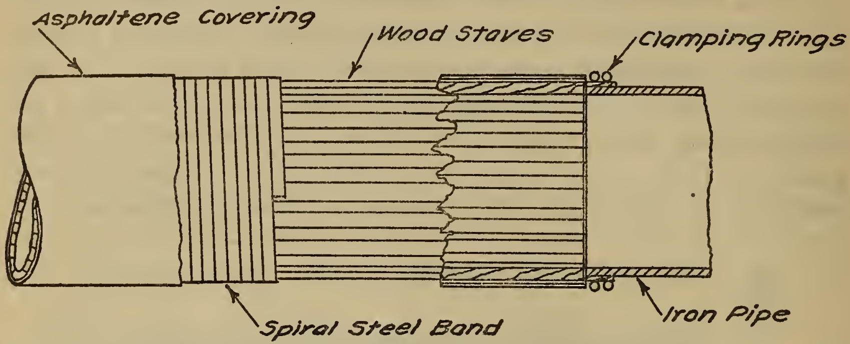

FIG. 18.—*Construction of Wyckoff stave pipe, showing connection to iron pipe*

The Metropolitan Water Board of Boston has used a type of wooden joint shown in Fig. 19. This joint is simple in construction, consisting of a one-half inch wooden liner made of overlapping sections of wood, the ring thus formed being wound with canvas impregnated with paraffin. The purpose of this is to prevent possible metallic contact between the ends of the pipes. The wooden staves are of clear white pine, planed to fit the curvature of the pipe, and are driven in by a special driver to prevent splintering. Any leaks that may develop are stopped with white-pine

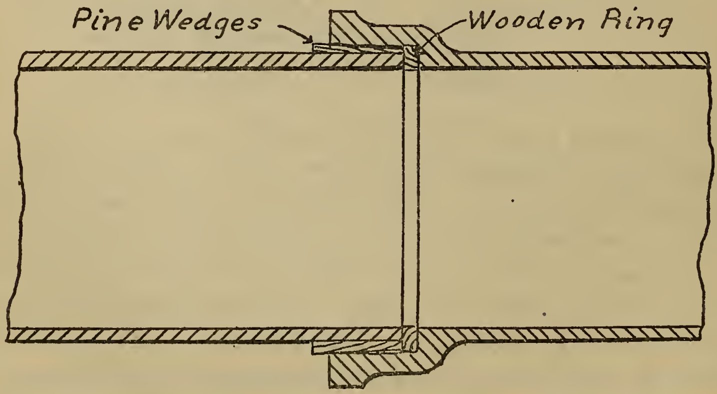

FIG. 19.—*Type of insulating joint used by Metropolitan Water Board of Boston.*

wedges. These joints have been found to be very satisfactory up to about 75 pounds pressure. Higher pressures sometimes cause moderate leakage through pores of the wood, and this has been overcome by dipping the inner ends of the staves in red lead. In some cases the staves are reinforced by an iron band clamped around the spigot end of the pipe. Usually a slight change is made in the castings where this joint is to be inserted, the spigot end being cast without bead and the inside of the bell smooth without groove.

The cost of these joints has been given as ranging from $5 to $12 when installed in new lines, but when installed in old mains the cost would be much higher. The resistance of this joint is ample under all circumstances that may arise, but the relatively short leakage path would often make it necessary to use the joint with greater frequency than would be necessary with joints having a long leakage path.

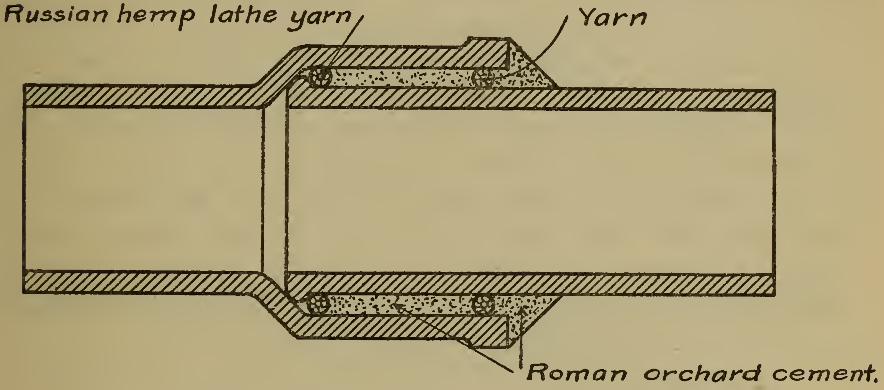

Fig. 20.—*Cement joint used by Cambridge Gas Light Co.*

Cement joints have been given a variety of forms, and one which has been used successfully for years by the Cambridge Gas Light Co. is shown in Fig. 20. In making this joint the inner ring of hemp is chosen exactly the right size to fill the annular space between bell and spigot, and this is rolled in when the pipes are set together and driven hard with the calking tool. As usually made by the Cambridge company no special attempt is made to keep the metal of the two adjacent lengths of pipe apart; notwithstanding this fact, the resistance of the joints has, on the whole, been high enough to prevent the accumulation of any considerable amounts of stray currents, and as a consequence this system has never been troubled by electrolysis, although the pipes of the Cambridge Water Co. are said to have suffered severely.

After thoroughly tamping the ring of hemp into place the cement is carefully worked into the joint with trowel and calking tool until the space between bell and spigot is filled flush with the face of the bell. Another turn of hemp the same as the first is then laid against the cement and driven in with the calking tool just under the edge of the bell. The cement is in this way rendered very compact, and it is claimed that on this feature depends in large measure success of the joint. A collar of cement is finally laid over the outer ring of hemp to protect it from rot. If success is to be achieved with this joint, great care must be exercised in the making of the joints. Perfect cleanliness of the inside of the bell and outside of the spigot is necessary, and all loose scale and sand should be removed before the cement is put in place. Only the best quality of cement should be used and this should be thoroughly mixed and tamped into the joint with the greatest care.

In some cases careful bedding of the pipes is important, as the cement joint is much less yielding than lead, and if any considerable lateral movement of the pipes takes place it is liable to break the pipe, the strength of a well-made joint being as a rule greater than that of the pipe itself. In some instances, instead of making every joint of cement, every third or fourth joint only is made of cement, the others being lead. Except in extreme cases this seems likely to prove practically as effective in minimizing electrolysis troubles, and it has the great advantage that the lead joints impart a flexibility to the system that will greatly reduce troubles due to lateral motion of the pipes.

The principal defect of the joint just described from the point of view of protection against electrolysis lies in the fact that no provision is made for preventing metallic contact between the bell and spigot end of the pipe. In order to guard against this a modified construction, shown in Fig. 21, can be used. This is the same as Fig. 20 except that an insulating ring *A* of rubber or fiber or other suitable material is inserted to prevent actual metallic contact between the ends of the pipe. Such a joint should answer all requirements for ordinary service where joints are used at very frequent intervals, so that the drop of potential across the joint is not great enough to require a long leakage path.

The use of leadite for joints has been confined chiefly to water mains, and for such service some prefer it to any other material, although it has not always met with favor. This material is melted and run into the joint after the manner of a poured-lead joint. It is cheaper than lead and some claim that it makes a better joint mechanically, but many dissent from this view. It often happens that when the joints are first made a large proportion of them will show considerable leakage, but in the presence of water they seem to have a tendency to seal themselves up and the leaks will usually cease entirely within a day or two.

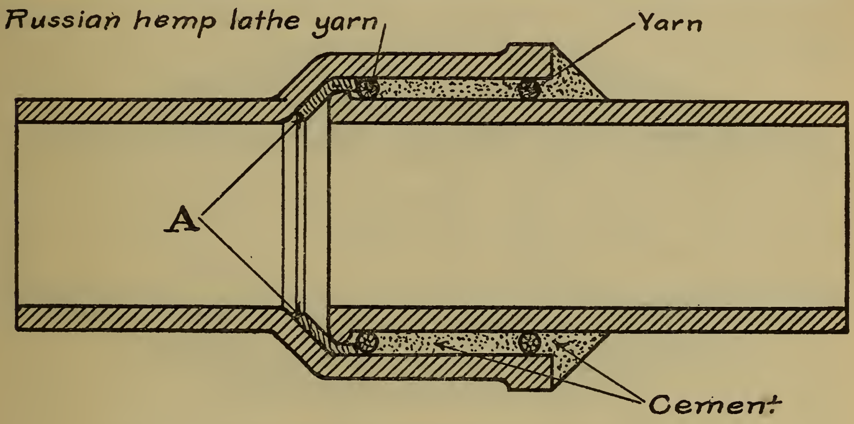

FIG. 21.—*Cement joint*

It is very important to see that a dense mass completely fills the joint, and it is lack of care in this respect that is probably responsible for most of the trouble with leaky joints. The runner used in pouring the joint should be so designed that there will be a head of 8 to 10 inches above the joint. If the material is at proper temperature this head is usually sufficient to insure a dense homogeneous mass of leadite in the joint. As already noted, the resistance of leadite is very high when first run, but after lying in the ground for some time its resistance decreases greatly, and until further experience has been had we would not recommend them unreservedly as suitable for preventing electrolysis, although they may be found valuable for this purpose.

(*h*) *Increasing the Length of Leakage Path Around Joint.*—Inasmuch as short insulating joints are much easier and cheaper to build than long joints, it is well to discuss here some possible means whereby a long leakage path may be given to a short insulating joint and thus combine in one joint a certain measure of the economy and ease of construction of the short joint and the greater protective tendency of the long joint. A joint embodying these features is shown diagrammatically in Fig. 22. In this case the insulating joint proper between the bell and spigot is made with cement in the usual way, care being taken to prevent metallic contact between the ends of the pipes. After the joint is finished, the ends of the pipe adjacent to the joint for a foot or two, on either side of the joint, or farther if the voltage drop is likely to be high, is painted over with a coat of pitch applied hot, and over this is wound a band of paper, cloth, or other fabric, which in turn is painted over with another coat of pitch, and so on until a layer of from 1 to 2 inches thick is obtained.

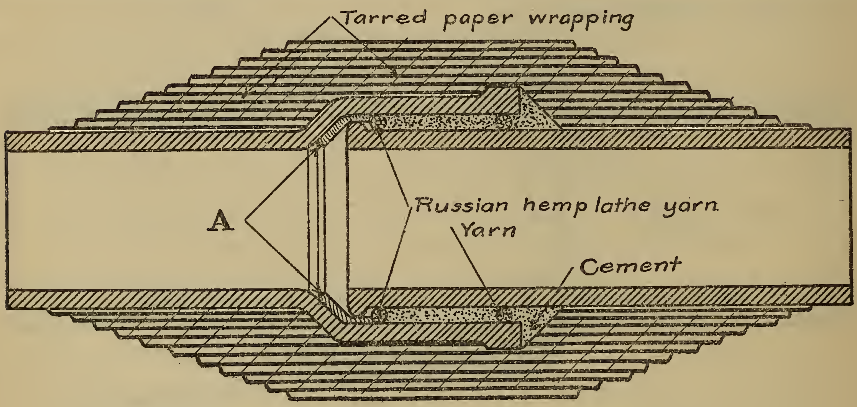

FIG. 22.—*Cement joint with long leakage path*

The expense of applying a coating of this character over a short length of pipe is small, and laboratory tests indicate that if carefully applied and made an inch or two in thickness it can be relied upon to remain effective for a number of years at least. That its life is limited, however, is indicated by the tests referred to in the early part of this paper, which show that moisture will slowly but surely penetrate the coating and when it finally reaches the surface of the pipe electrolysis begins and ultimately destroys the coating. The thicker the coating is made the longer time will be required for moisture to penetrate it, and, because of the higher resistance, the slower will be the electrolytic action even after the current path through the coating is established. Such a coating, if made an inch or more in thickness, would undoubtedly last, in most cases, as long as the pipe itself.

Another method of increasing the length of the leakage path around an insulating joint consists in surrounding the joint with a wooden trough several feet long and leaving a space of several inches on all sides of the pipe, this space being filled with pitch. This makes a very permanent insulating section and can be made as long as desired.

9. PIPE DRAINAGE.

The system of electrolysis mitigation which has received wider application in this country than any other method is that which is best characterized as the pipe-drainage system. The essential features of this system consist in connecting conductors at suitable points of the pipe system where the latter tend to become positive to the earth to take the current off the pipe through these conductors instead of permitting it to discharge directly into the earth. The conductors may take the form either of bonds connected directly between the pipes and tracks wherever the pipes are found positive to the tracks, or the conductors may take the form of special feeders running directly from the negative bus bar out to various points on the pipe system.

(*a*) *General characteristics of Pipe-Drainage Systems.*—Before describing the different modifications of this method of reducing electrolysis it is well to point out some of the general features inherent in all of its different modifications. It will readily be seen that, since damage takes place on the pipes where the current is discharged from a metallic conductor into an electrolyte, if all of the current could be taken off the pipe through metallic paths without introducing any new elements of danger to the system to which the cable is attached or to any other system, the pipe-drainage method would prove very effective in relieving electrolysis trouble. Such a condition, however, can not be realized in practice, and in a practical working out the pipe-drainage system is subject to certain drawbacks which seriously limit its field of usefulness.

Among others it has been objected that the pipe-drainage system is not a permanent system, but that it requires constant watching and changing whenever there is a marked change in either the distribution of the pipes to which the cables are connected or when there is any material change in the track network or in the distribution of load on the track. This objection is undoubtedly a valid one in most instances and is a serious one in those cases where uninsulated feeders or taps are connected to the pipes, since, as will be explained later, when such uninsulated connections are used, it is impracticable to control the distribution of current in them. If, however, insulated feeders are run from various points in the pipe to the bus bars, a large measure of control of the current distribution in the pipes can be secured by changing the resistance of the cables or their connections to the pipes, in which case the difficulties arising from the changes in the pipe system or in the street railway load become much less serious, although they must always be carefully watched and taken care of.

The same may be said, however, to hold true to a greater or less extent for practically any system of electrolysis mitigation that can be applied, although these difficulties are probably more serious in the case of a pipe-drainage system than in the different forms of track drainage which will be considered later, because the latter are affected only by changes in the street railway load and are independent of the extent and distribution of the pipe systems.

A second objection and one which is inherent in the pipe-drainage system, is the fact that whichever form of it may be applied, it will necessarily increase to a greater or less extent the amount of current carried by the pipes, and this is accompanied by a correspondingly increased danger of trouble developing on high-resistance joints or in unlooked for places.

In all cast-iron pipe systems using lead joints it will be found that the lead joints not infrequently develop high resistances which may reach values equivalent to the resistance of from several hundred to many thousand feet of pipe and it will be quite evident that if any considerable amount of current is flowing on the pipes the drop on these high-resistance joints will be so great that the leakage current about the joint will be sufficient to cause rapid destruction of the pipe on the positive side of the joint. Further than this, it has become quite common practice in recent years to use cement joints or other insulating joints in pipe systems, particularly in cast-iron, natural-gas mains, and since cement joints have a very high resistance practically all of the current flowing on the pipe would be compelled to leak around such joints, thereby doing great damage unless the current is kept extremely small. For this reason the application of the pipe-drainage system must necessarily be limited to those systems in which it is known that joints of high resistance do not occur, or else special precautions must be taken to shunt around such high-resistance joints as may exist.

Another objection to pipe drainage is that the application of the drainage to any one system of underground structure lowers its potential with respect to neighboring metallic structures, thereby tending to injure the latter, and the greater the amount of current drained from one system the greater will be the danger thus occasioned to the other structure. It is evident that two underground pipe systems are so much more intimately associated with each other than is a pipe system and a railway system that a much smaller potential difference between such underground pipe systems must be maintained than is required between a pipe system and a railway line.

It is of the highest degree of importance, therefore, that nothing should be done which would tend to set up any appreciable potential difference between two underground metallic structures occupying the same territory. In view of this fact, if two or more utilities occupying the same field all attempt to drain their networks so as to keep them neutral or negative to surrounding structures, the drainage conductors of any one system tend to set up a condition of danger to the neighboring system, which calls for the addition of more copper to take care of the latter. This results in establishing a condition of competitive drainage which will inevitably become ineffective as a preventive of damage by electrolysis and will often involve greater expense than an effective mitigative system applied to the railway tracks. This difficulty might be avoided to a large extent if it were possible to treat all of the underground metallic structures as a single network of conductors, to be drained under the direction of a single authority, but in general such an arrangement is impracticable.

There is another danger growing out of the presence of electric current on the pipes, which is greatly increased by drainage, and this danger may assume serious proportions when this method is unwisely used. This danger arises from arcing at points where the pipe line or its connections are opened for any reason, or where different pipes or cables at different potential make momentary contact. To guard against this danger it is usually necessary to bond across the proposed break in any gas pipe to which drainage is applied. Failure to provide such a bond, or the accidental opening of the bond while the continuity of the pipe is interrupted is liable to ignite escaping gas with possible dangerous results to life and property. In addition to this, the danger from the formation of electric arcs by transient contact between different pipes or cables entering buildings is greatly increased by drainage, and this gives rise to a fire hazard that may at times be serious. Manhole explosions are probably frequently caused by transient arcs caused by creeping of cables in ducts and the danger from such arcs is increased by drainage.

Another danger that arises from the presence of a heavy current flow on the pipes, which would always be augmented by pipe drainage, is the danger from the overheating of service pipes and their connections. Cases have been brought to our attention in which metallic connections between gas and water pipes in gas water heaters have been heated red hot by excessive current flow therein; and we have also met cases in which lead service pipes have been melted by excessive current flow caused by overdrainage. Such cases are, however, quite rare and are due to the abuse rather than to intelligent use of drainage.

The draining of lead cables is under most circumstances less objectionable than the draining of pipes. The cables are usually continuous conductors, and the troubles arising from high-resistance joints are not encountered. Further, when cables are laid in conduits that are kept free from standing water they are in much less intimate contact with the earth than are pipe systems, and consequently the application of drainage to such cables does not induce as heavy current flow therein as caused by the drainage of pipe systems. When applying drainage to cables it is necessary to drain just sufficiently to prevent the cables from being appreciably positive to the pipes for any considerable part of the time, and precautions should be taken not to overdrain the cables, as such drainage may create many of the dangers mentioned above with reference to pipe drainage. This is particularly true in case the cables are so located that the conduits are filled with water a considerable portion of the time. Under such conditions the drainage of lead cables is quite as objectionable from the standpoint of the safety of adjoining metallic structures as the drainage of underground pipes.

Another objection to the drainage of underground structures, which may often become serious, arises from the tendency toward the production of an excessive amount of alkali at the surface of the negative electrode embedded in the earth. This will occur to a greater extent in some soils than in others, depending upon the chemical content of the soil. This danger will be greatest where the soil contains large amounts of the salts of the alkali metals, which condition not infrequently exists. The concentration of an alkali at the negative terminal will have no detrimental effect in the case of iron pipes, but it may give rise to a large amount of soil corrosion in the case of lead service pipes and lead cables. It is necessary to guard against this condition unless it is known that soil conditions are such as not to give rise to any serious increase in the alkalinity of the soil under the voltage conditions that would exist.

Not the least objection to pipe-drainage systems, however—and this applies to all methods applied only to the pipe systems—is the fact that they tend only to relieve the symptoms rather than to remove the cause of the trouble. Pipe drainage is therefore of the nature of a palliative rather than a remedy. In general, our study of the pipe-drainage method has convinced us that while it may under certain conditions be used to advantage as a secondary means of lessening the trouble, its installation in connection with most city networks as a principal means of electrolysis mitigation is an unwise procedure. We would point out, however, that there are special cases, such for example, as that afforded by an interurban line paralleling a single large main, particularly of riveted steel, in which practically all of the objections mentioned above in connection with pipe drainage do not apply, and in such cases pipe drainage may offer the best and most economical solution of the electrolysis problem that can be had. Our objections to pipe drainage, therefore, are not against the system itself, but rather against its use under conditions to which it is not adapted, which latter, as already mentioned, include the greater portion of city networks where a number of utilities are operating in the same district.

In its practical working out, pipe drainage exhibits two opposing tendencies, namely, (1) the reduction of the difference of potential between the pipes and rails in the positive areas with consequent reduction of damage at these points, and (2) an increase of the current flow in the pipes throughout the entire system, thus increasing the danger of trouble at bad joints or other places where two pipe systems or parts of the same system are electrolytically discontinuous, as well as increasing danger of fires and explosions as already outlined. As a rule, in the early stages of its application the effect has been beneficial, since it reduces the trouble where it has been most serious and tends to cause it to spread out in regions where it had not previously been in evidence.

In small systems where the total current flow is comparatively small the net result may be beneficial, a reduction of danger in the positive areas being greater than the increased danger in the more remote localities. As the system grows and the load increases more and more current must be drawn from the pipes in order to prevent their becoming positive to the earth, and the consequent damage due to the influences above mentioned will become of greater and greater moment; any further extension of the pipe-drainage system then becomes a menace to the network and particularly to other networks occupying the same territory. It is largely because of the slow and obscure manner in which trouble develops that this method is so widely used. It transfers the trouble from where it has been most evident to new localities where it may require several years to manifest itself anew. Its early results are likely to create a more favorable impression than its value as a permanent protection will justify.

In order to avoid the more serious effects resulting from increase in the current flow in the pipes it has been proposed in some of the more recent installations to limit the current flow in the pipes by increasing the track conductivity. Under this plan, when the total drainage current reaches a fixed percentage of the total railway load, say 10 per cent or thereabouts, the track conductivity is to be increased by copper cables in order to keep the drainage current below the prescribed limit. In some systems which we have been investigating in which the pipe-drainage system has been applied, it has been found that in order to reduce the potential of the pipes to sufficiently low values it was necessary to draw from the pipes from 40 to 50 per cent or more of the total railway load. It is evident that if one attempts by means of ordinary uninsulated negative feeders to increase the conductivity of the track to a point that will reduce the total leakage to 10 per cent, the cost of the copper cable required would be so great as to render the plan altogether impracticable. If, however, the potential gradients in the track are reduced by some other means as described in detail in a later part of this paper, it will be readily practicable to get them to such low values that the difficulties attending the application of the pipe-drainage system will be greatly reduced.

Under such circumstances the pipe-drainage system may be of value as an auxiliary method to be applied, in certain special cases where the chief objections to this system do not exist, to relieve such electrolysis trouble as might still occur after the potential gradients in the railway return have been reduced as far as is economically practicable by some other means. While it is true, as pointed out in a later part of this paper, that such a reduction of potential gradients in the negative return can in most cases be made to take care of the electrolysis situation without the application of any additional measures, there are, nevertheless, cases in which it might be advantageous to apply a limited amount of pipe drainage as an auxiliary means of protection. The method should therefore be regarded as a practicable auxiliary to the methods described in succeeding sections of this report and is of sufficient importance to make it desirable to outline here in some detail the different forms which a pipe-drainage system may take and discuss briefly the principles on which the design of such systems should be based.

(*b*) *Direct Ties Between Pipes and Tracks.*—The first and simplest form of pipe drainage that was used is that shown diagrammatically in Fig. 23. This consists simply in connecting short taps between pipe systems and railway track where the two run in close proximity to each other and where the pipes tend to become positive to the tracks. As a rule, the procedure in installing these taps has been to make a voltage survey throughout the affected district, and wherever the pipes are found to be strongly positive to the tracks a tie is put in connecting the pipes and tracks together, the intention being to install these ties at sufficiently frequent intervals to bring the pipe and track systems to practically the same potential throughout.

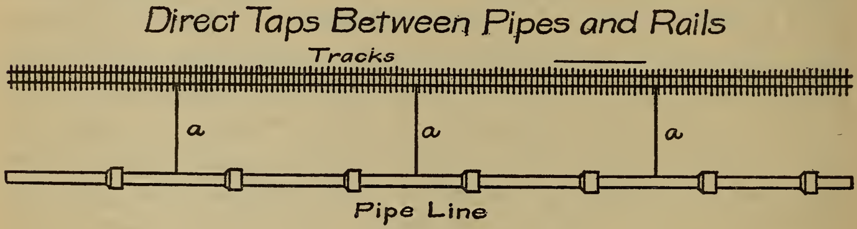

Fig. 23

The chief merit of this system lies in the comparatively small amount of copper required for its installation. This is in a large measure offset, however, by the relatively large amount of labor involved in making the connections and it also has other disadvantages which render it much less effective than some other modifications to be described later. In the first place, the putting in of copper bonds of this sort at any point where an appreciable difference of potential is found between pipes and rails will, in the course of time, lead to a great complexity of such connections. Furthermore, since these connections are in practically all cases entirely underground, it is not feasible to make frequent inspections as to their condition or to make measurements of the current which they are carrying and in consequence of this, after the system has been in use for a few years it is practically impossible to get definite information as to the actual condition of the system as regards what bonds may be connected or how much current may be flowing in the different parts of the pipe system.

Another difficulty with this system lies in the fact that the drop of potential on the pipes is always equal to the potential drop on the negative return between any points of connection to the track, and unless special precautions are taken to make the drop of potential in the negative return very low, this will necessarily lead to heavy current flow in the pipe, thus giving rise to numerous possible troubles growing out of such excessive current flow on the pipes, as already described.

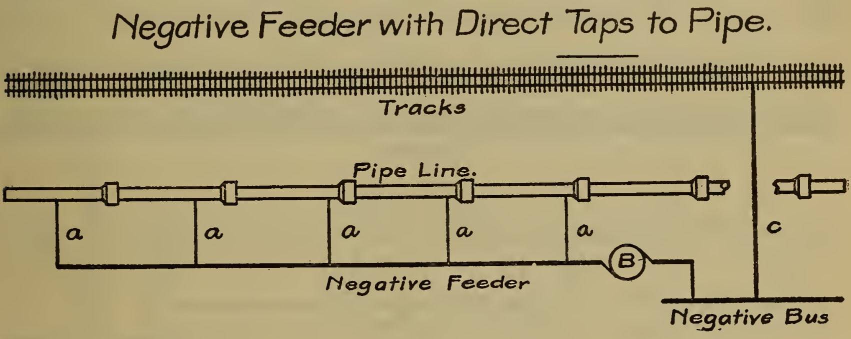

FIG. 24

Another objection lies in the fact that should any discontinuity occur in the track between two adjacent ties, the entire railway current would be compelled to flow around through the pipes, and in case there were any high-resistance joints in that portion of the pipe, rapid destruction of the pipes would inevitably occur.

A fourth objection to this type of pipe-drainage system lies in the fact that it is impossible to control the distribution of current flowing on the pipe system so that excessive current flow in certain portions of the pipe network can not be prevented.

Taken altogether, the objections to this type of pipe drainage far outweigh the single advantage of low cost of copper and we do not consider it a desirable system to install under any circumstances.

(*c*) *Drainage by Uninsulated Feeders.*—A modified form of pipe drainage which has frequently been used and which is less objectionable than the one just described is shown in Fig. 24. In this system instead of tying the pipes directly to the tracks at frequent intervals a copper cable is run from the negative bus along the pipe line and tapped to it at frequent intervals by taps *a*, *a*. This has the advantage over the system just described in that the pipe system is entirely independent of the tracks, so that the bad joints either in pipe or tracks between taps would in most cases be less serious.

The total current drawn from the pipes can be controlled by installation of the booster *B* in series with a negative feeder at the power house or, to some extent, by varying the resistance of the cable. Here, as in the preceding case, it is not practicable to control the distribution between the different sections of the pipe. The control of the total current by means of the booster will, however, be objectionable because of the complication and cost of the necessary booster equipment.

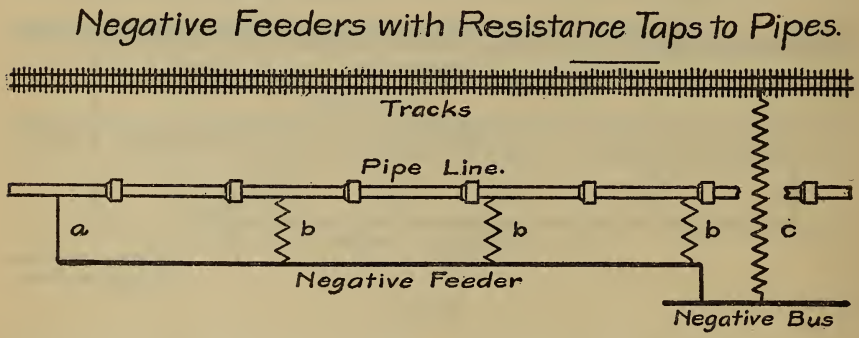

Fig. 25

Another objection to this form of pipe drainage lies in the fact that the potential gradient on the pipe is the same as on the negative feeder, and because of this the current density in the copper cable will be very low unless the potential gradients along the pipe system is objectionably high. The result would be a very uneconomical use of copper, leading to high cost of installation in comparison with the benefits obtained.

(*d*) *Drainage by Insulated Feeders.*—In order to overcome certain of the objections mentioned above the modification shown in Fig. 25 might be used, although so far as we are aware, a system embodying these features has not heretofore been installed. In this case a cable is run along the pipe line as before, but instead of tying the cable directly to the pipe line at frequent intervals, a direct connection to the pipe is made at the extreme end of the cable, *a*, and then at intermediate points *b*, *b*, connections are made between the cable and the pipe through suitably designed resistance taps. These might take the form of short steel cables properly proportioned to give the desired resistance and similar in construction to those described later in connection with the discussion of track drainage systems.

It is possible by properly adjusting these resistances to secure a fairly equal distribution of current between the different taps regardless of the size of the feeder cable. In this way a better distribution of the current in the pipe system can be secured whereby a heavy current on the pipes at any point can be to a large extent avoided and at the same time the copper cable can be designed for maximum economy, and this greatly cheapens the installation. In such a case, however, the drop along the cable will, as a rule, be much greater than the drop along the pipe, and this will result in gradually increasing drop on each of the taps as we approach the power house. By the time the power house is reached, the drop between the pipes and the negative bus may become quite large. We can not, therefore, connect the tracks directly to the bus bar, as in Fig. 24, as in that case the pipes near the power house would become strongly positive to the tracks and there might be a large discharge of current from the pipes to the tracks in that locality. In order to avoid this, it is necessary to raise the potential of the track above the bus bar by about the same amount as the pipes, and this is accomplished by the installation of a low resistance tap between the tracks and negative bus bars and at the power houses, as shown in Fig. 25.

Still another modification of pipe drainage by means of insulated feeders is shown in Fig. 26. In this case, instead of running a single feeder along the pipe line to be protected, separate feeders are run from the power house to various points on the pipe line. These feeders must either be given sufficient cross section to carry the desired current with a total drop no greater than the rail drop between the power house and the extreme point at which the feeders run, or else boosters must be installed in the feeder in order to force the desired current through them. In the latter case, a considerable economy in copper is secured, but at the expense and complication of the booster equipment. This difficulty is eliminated in the modification shown in Fig. 27. In this case the different feeders are designed to have practically the same resistance so that substantially the same current will flow in each one without any great difference of potential between the points at which they are connected to the tracks and, subject to this condition, the feeders are designed to give maximum copper economy. This, as a rule, involves a much greater drop on the feeders than is permissible along the tracks, and in order to prevent a large difference of potential between pipes and tracks near power house and also to secure the necessary drop of potential to force the desired current over the drainage cables a resistance tap *C* is installed the same as in Fig. 25.

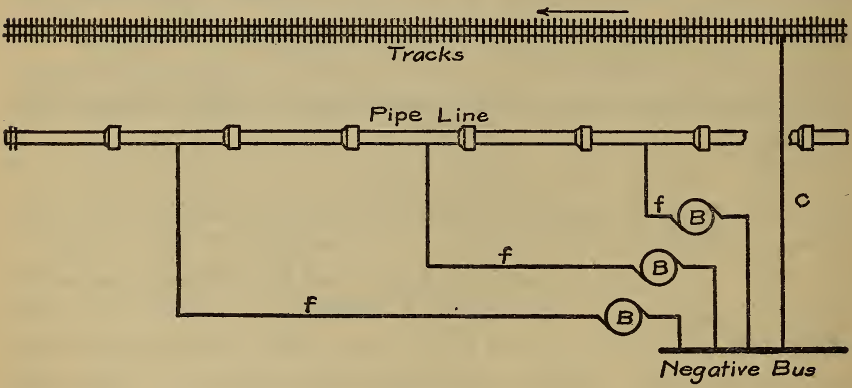

FIG. 26

For reasons given in detail later in connection with the discussion of the cost of insulated feeder systems in general, the pipe drainage systems shown in Figs. 25 and 27 will prove the most economical of any that can be installed, and at the same time they permit an accurate determination of the distribution of current in the different parts of the pipe network, and also permit a considerable amount of regulation of such current distribution through the adjustment of the individual feeders or resistance taps. This control feature is of the greatest importance, since only in this way can dangerously heavy currents in the pipes at certain points be avoided.

Even these systems, however, possess the drawbacks that must be common to all pipe drainage systems, namely, that unless the potential drops in the tracks are kept within reasonable limits, large currents may have to be drawn from the pipes in order to keep them from becoming too strongly positive to the earth. Hence, the pipe drainage system even in its best form can not be expected to give satisfactory results unless installed with due regard to its influence on neighboring structures, and particularly unless potential drops in the tracks are first reduced to such low values that only a very small amount of current needs to be taken from the pipes. The means whereby such low voltage drops in the negative return may be secured in the most economical manner are discussed in a later section of this paper.

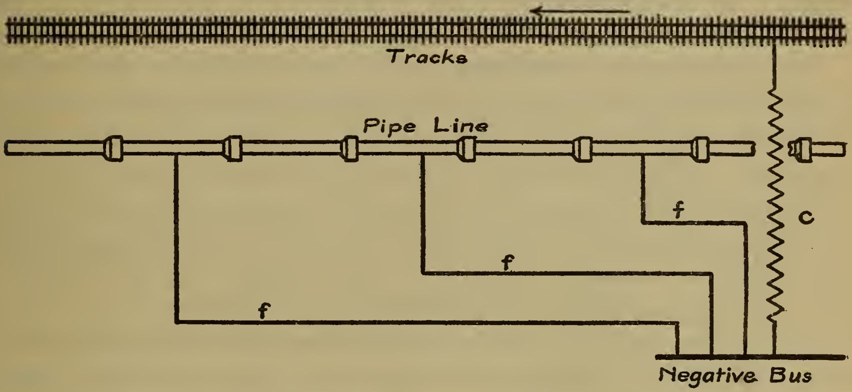

FIG. 27

10. SUMMARY OF DISCUSSION OF METHODS OF MITIGATION APPLICABLE TO PIPES

The discussion presented above relating to methods of mitigation applicable to pipe systems leads to the conclusion that of the various methods that have been tried none are suitable for general use as primary means of preventing electrolysis troubles. The methods of chemical protection, cement coatings, cathodic protection, and conducting coatings should be regarded as substantially worthless in their present state of development. Surface insulation of pipes by means of paints or dips is not much more reliable, but insulation by putting the pipes in troughs or conduits filled with pitch may be used in special cases where the expense would be justified. The practice of placing all pipes as far as possible from railway tracks affords a certain measure of protection of which advantage should always be taken wherever practicable in laying new lines or relaying old ones, and the use of electric screens is often a valuable expedient in taking care of acute local cases of trouble in existing mains. These methods, with the exception of that relating to the proper location of pipes in new work, are suited only to special conditions, however, and are not usually to be considered as important factors in any general plan for electrolysis mitigation.

Pipe drainage is sometimes useful but should be used with proper restriction and with due precautions against setting up any dangerous condition either in the system drained or in neighboring systems. In general, in city networks where there are a number of independent underground systems to be protected, pipe drainage should be used as little as possible, the chief reliance being placed on mitigative measures applied to the railway negative return. The drainage of lead cable systems will, however, usually be desirable, but these should always be drained by means of suitable insulated-feeder systems so arranged as to drain the least practicable current from the cables in order that neighboring structures may not be subjected to unnecessary danger thereby. The most valuable mitigative measure that can be applied to pipe systems consists in the proper use of insulating joints, and the extensive use of such joints should be encouraged in new work and in making repairs. Precautions are necessary in their use, however, as set forth in the preceding discussion.

None of the methods of mitigation available for application to pipe systems are, except in special cases, to be recommended as principal means of mitigation, but rather as auxiliary or emergency measures, which may be used in connection with, and supplementary to, measures applied to the railway return systems for reducing stray currents to the lowest practicable minimum. Methods for accomplishing this end will be discussed in the next section.

IV. METHODS OF MITIGATION APPLICABLE TO RAILWAY NEGATIVE RETURN

None of the systems of electrolysis protection mentioned above have to do with the nature or condition of the street railway return circuits, and in the practical working out of such methods the railway return system is often ignored. The currents are permitted to flow away from the tracks without restriction, and the sole purpose of the methods outlined is either to prevent their entrance into the pipes or to provide means for their exit with as little injury to the pipes as possible. It would appear more logical to attack the problem by beginning at the source of the evil and prevent, to a large extent at least, the leakage of the currents from the railway return conductors into the earth. This is the more emphasized by the fact that in the past, where such mitigative measures have been applied to the pipes, the burden of providing the protection has usually fallen where it does not properly belong, viz, on the injured party and not on the party causing the injury. We shall now consider what measures may be applied by the street railway companies to their own properties with the view of removing, or at least greatly reducing, the cause of the trouble.

1. ALTERNATING-CURRENT SYSTEMS

The proposition to use alternating current for street-railway traction purposes need hardly be discussed here. If alternating current were used, the amount of electrolysis that would occur would in most cases be not more than 1 per cent of what it is with direct current. In the case of lead pipes the corrosion may be greater than this, but the experimental data available show that there is little likelihood of its exceeding this percentage under practical conditions.

The objections to the substitution of alternating current for direct current in the case of systems already installed in large cities are so obvious and so serious that the question needs no discussion, particularly since the problem of electrolysis protection can be taken care of by other means. In the case of suburban or interurban systems, on the other hand, where alternating current possesses certain advantages which for other reasons often justify its use, the fact that such a system will be comparatively free from electrolysis troubles is an additional argument in favor of its use.

This question of electrolysis, due to stray currents from interurban roads, is becoming increasingly important as pipe systems are installed or enlarged in small towns along the route, and particularly because of the steadily increasing number of pipe lines being installed throughout the country. In such cases the alternating-current system of traction may well be regarded as a satisfactory solution of the electrolysis problem, although at the present time the importance of this protection along interurban lines is not great enough to be by any means a deciding factor in the choice of systems.

2. DOUBLE-TROLLEY SYSTEMS

The double-trolley system of electric traction as at present used in Cincinnati, and the corresponding underground conduit systems as used in Washington and in parts of New York City, eliminate almost completely the danger of electrolysis, the small leakage which occurs being of no practical consequence. The chief objections to its use are the cost of installation and the increased operating difficulties which it involves. The cost of installation, which is very great, does not appear to be justified merely as a means of electrolysis protection, inasmuch as a very satisfactory degree of protection can be obtained by other and much more economical means.

3. USE OF NEGATIVE TROLLEY

Practically all street-railway systems in this country are operated with positive trolleys. Under such conditions the stray current is taken up by the pipes over a relatively large area and discharged within a comparatively small area, commonly called the positive area, near the power house. It is obvious, therefore, that the current density within this small positive area will be much greater on the average than in the much larger negative area. If the polarity of the trolley were reversed, the positive and negative areas would be interchanged without affecting to any considerable extent the intensity of the current at any point. We should then have a comparatively low average density of current discharge from the pipes throughout a much larger positive area. The total amount of corrosion would not be materially affected, but its distribution over the larger area would tend to reduce the intensity of damage at any particular point, so that the average life of the pipes would be increased and trouble would be much slower in developing.

Aside from the fact that in some cases the increased life of certain of the pipes might be such that they would endure until they would have to be removed anyway for reasons other than their failure, about all that can be said in favor of this proposal is that it postpones the time when serious trouble will develop. On the other hand, most engineers would prefer to have the trouble more localized, as it is under present conditions, where it can be more carefully watched and more effectively controlled. Furthermore, this reversal of trolley polarity will generally impose serious hardship on cable-owning companies which have already installed a drainage system for the protection of their cables. This method does not, therefore, appear to be worthy of serious consideration in the present instance.

4. PERIODIC REVERSAL OF TROLLEY POLARITY

Another proposal that has been advanced has for its object the attainment, as far as practicable, of the electrolytic conditions which prevail with alternating currents, without discarding the direct-current method of electric traction. If an alternating current flows from iron into soil, there is, during any half cycle in which the iron is positive, corrosion of the iron just as in the case of direct current, but during the succeeding half cycle the corroded iron is again plated out as metallic iron on the surface of the pipe. If the efficiency of both corrosion and deposition is 100 per cent, there will be no perceptible corrosion of the metal surface, and in the case of ordinary alternating currents this condition is very nearly realized in practice.

Experiments have shown that even with very low frequencies of reversals, such as once in 24 hours, a large measure of this effect persists, and the ultimate amount of corrosion is much less than would occur if the polarity is maintained always the same. It has therefore been proposed to reverse the polarity of the trolley at stated intervals, as, for example, once every 24 hours, as a means of reducing electrolysis troubles. If the reversals are made with sufficient frequency to give effective protection, the method is open to the objection that it introduces a complication into operating conditions that does not appear to be justified by the benefits that would result, particularly where several substations are being operated in parallel. Where only a single substation is used, a reversal of polarity once in 24 hours would be entirely practicable and would undoubtedly be decidedly beneficial.

Extensive experiments at the Bureau of Standards show that with daily reversals of polarity the corrosion in the case of iron pipes at any particular point will be only about one-fourth as much as when the current flows continuously in the same direction. For lead pipes and cables the polarity would have to be reversed much more frequently in order to reduce the corrosion at any point to less than 50 per cent of that which would occur with unidirectional current.

5. REDUCING POTENTIAL DIFFERENCES IN THE UNINSULATED PORTION OF NEGATIVE RETURN

Turning now to a consideration of what may be accomplished in the way of providing an adequate return circuit for the railway currents we find a number of possibilities available. In considering these methods it is necessary to bear in mind that the fundamental condition to be realized in order to reduce the leakage of stray currents into the earth is *not the maintenance of the lowest possible resistance in the negative return but the minimum differences of potential between different parts of the grounded track network.*

The two conditions are not necessarily identical, depending as they do on the character of the negative return system used. The various possible methods of thus reducing track gradients to a satisfactory value all have for their primary object the taking of the current direct from the track through the agency of negative feeders, and they are therefore classed in one general group under the name of "track-drainage systems." These track-drainage systems present several separate practical embodiments, the chief of which are (*a*) the proper construction and maintenance of track to secure the full benefit of the conductivity of the rails, (*b*) grounding of tracks and negative bus, (*c*) the use of uninsulated negative feeders in parallel with the rails, (*d*) the use of insulated negative feeders without boosters, (*e*) the use of insulated negative feeders with boosters, (*f*) the three-wire systems, and (*g*) the use of a proper number of substations so located as to take the current from the tracks so as to combine in greatest degree economy of distribution of power and reduction of leakage current from the rails. These different systems are discussed separately below.

6. CONSTRUCTION AND MAINTENANCE OF WAY

Proper maintenance of the track in order to secure high conductivity is everywhere recognized as a necessary condition in electric railway operation, but it does not always receive the attention that its importance justifies. In the matter of joints alone there is a very wide diversity of practice. In recent years, however, engineers have rapidly come to recognize the difficulty of maintaining a proper state of track conductivity by merely bridging the joints with short copper bonds. Such construction is still widely used, but it is finding much less favor than formerly, and in many systems, particularly where the traffic is heavy, these methods of shunting the joints are used, if at all, chiefly as secondary expedients. The tendency in such cases is to make the joint itself electrically continuous rather than to shunt around it, although both methods are not uncommonly combined.

The methods whereby more or less perfect continuity of the joints is obtained embrace the various types of welded joints such as electric welds, Thermit welds, etc., and those joints in which a second metal such as zinc and its alloys are employed to form the junction. Of these latter the well-known Nichol joint made by pouring molten zinc between the fishplates and the rail ends is one of the most effective, and has given very satisfactory service for a number of years. The zinc is poured in after the fishplates are bolted on and the expansion of the zinc which takes place on solidifying makes a firm and permanent contact between the fishplates and rail ends. Joints made either in this way or by any of the various welding processes have, as a rule, a lower resistance when new than an equal length of rail, and for the most part have given good satisfaction in service, although some trouble has been experienced, particularly in welded joints, due to parting of the rails at the weld. Experience to date, however, indicates that these joints are very satisfactory in all cases where the tracks are laid in paved streets or otherwise suitably reinforced. As a precautionary measure, however, some engineers prefer to bond over all joints, also, and we understand that this is being largely done in St. Louis.

Cross bonding between the rails is also much resorted to as a means of maintaining track conductivity, and this is a very necessary precaution against the troubles arising from bad joints. If such cross bonds are properly installed and maintained at sufficiently frequent intervals, the deleterious effect of occasional bad joints is almost entirely eliminated. These cross bonds are usually placed at intervals of from 200 to 500 feet and these distances are sufficient if the cross bonds and rail joints are fairly well maintained.

All special work should be shunted by heavy cables capable of carrying all of the current passing over the tracks at that point. In many places this is the regular practice, but it is often neglected entirely or poorly maintained, and in some cases the drop across special work has given rise to very serious electrolysis. The remedy is so simple and effective that only carelessness can account for the existence of trouble of this nature.

The question of weight of rails is one that has not usually received the consideration which it deserves, particularly in the case of the T rails. At the present price of girder rails there is very little difference between the cost of rail and copper of the same conductivity. The conductivity of steel rails varies considerably, but on the average it will be about one-tenth to one-twelfth that of commercial copper. Hence, at the former figure with copper at 17 cents per pound and rails at $39 per ton the cost of a given conductance will be about 10 per cent greater if obtained by using copper cables in parallel with the rails than if it is obtained by the use of heavier rails. In the case of T rails costing $28 per ton the cost of a given conductance in steel rails will be about two-thirds that for copper. This is on the assumption that the extra labor cost of laying the heavier rails will about equal the cost of laying the copper cables. As to whether or not this is true will depend largely on local conditions, so that the above figures are only approximate.

An important factor which should be considered here, however, is the reduction in track and rolling stock maintenance charges that accompany the use of heavier rails. This is often sufficient to justify the extra expense of the heavier rails quite apart from any consideration of their higher conductance, and largely for this reason there has been a general tendency in recent years to use heavier rails. When we consider this fact in connection with the increased conductance of such rails there would appear to be good reason for using somewhat heavier rails than traffic conditions would usually call for in those regions near the power houses where it is important to secure higher conductance than would be afforded by the usual weight of rails.

The rail weights used in most large cities range for the most part between 80 and 120 pounds, so that we may consider that the approximate average weight is but little more than 100 pounds per yard. A double track of these rails having good joints has a conductance equivalent to about 4.5 million circular mils of copper. Standard rails are now rolled and in practical use weighing 137 to 139 pounds per yard and would have a conductance of about six and one-quarter million circular mils, or an increase over that of the average rails equivalent to about one and three-quarter million circular mils. It would therefore appear to be worth while in some cases, when tracks are being relaid near the power stations, to consider seriously the advisability of using much heavier rails than are usually adopted, the combined effect of improved track conditions and increased conductance being sufficient to justify the additional expense.

A properly constructed and drained roadbed is also a very effective aid in reducing the leakage of stray currents from the rails. The amount that can be accomplished in this way will, of course, vary greatly with varying conditions so that no specific recommendations can be made here, other than to point out that since the conductance of the leakage path is mainly dependent on the amount of moisture which is contained in the material forming the roadbed and the earth beneath, any construction which tends to reduce the average moisture content therein will reduce in corresponding degree the magnitude of the leakage currents. Indeed, we have made tests on long lines of track without intersections to cause complications, in which it was found that leakage from the rails had been almost entirely eliminated, the reason being that the road was so constructed that the leakage path from rails to earth was on the whole comparatively dry. We believe that much more could be accomplished by this means than is commonly supposed without materially increasing the cost of construction, although it must not be regarded as a satisfactory primary means of electrolysis mitigation.

7. GROUNDING OF TRACKS AND NEGATIVE BUS

The grounding of the negative bus or the tracks near the power house was one of the earliest expedients resorted to for the purpose of reducing the resistance of the negative return. Because of the decided tendency for such grounds to increase the flow of leakage current from the tracks it was early recognized that they might tend to increase electrolysis troubles, and in the majority of cases these ground plates have been abandoned. There are, however, a good many cases where such grounds still exist, so that their bearing on the electrolysis situation is an important matter. During the last few years, also, it has been seriously recommended by certain well-known engineers that this expedient of grounding tracks be carried much further, and, in fact, used as a means of eliminating electrolysis.

The method of procedure proposed by the advocates of this system is to lay ground plates several feet below the track and at frequent intervals throughout the stystem so as to secure as nearly as possible the perfect grounding of the tracks at all points. This proposal has been based chiefly on experiments which have been performed with small electrodes buried in the earth which showed that most of the resistance between such electrodes and the earth was found to be in the region very near to the electrode, owing to the small cross section of the current path at such points. From these experiments the conclusion was drawn that at a distance of 3 or 4 feet from such an electrode the cross section became so great that the resistance practically disappeared. It was therefore thought that if frequent ground plates were laid 3 or 4 feet below the track and connected thereto, the large cross section of the path offered for the discharge of current into the earth would cause the resistance of the negative return practically to disappear, and consequently the drop of potential in the earth would be so small that no appreciable current would be picked up by the pipes.

Our own investigations on this subject, which have comprised experiments with electrodes both of the size used in the investigation above referred to, and also with much larger ones, which are more comparable with conditions which actually exist in railway systems, and also the results of voltage surveys made remote from electrodes that might serve as sources of stray currents, have convinced us that the theory on which this method of protection is based is erroneous, and that the stray currents that would be introduced into the earth by the proposed ground plates along the track would greatly aggravate the trouble from electrolysis. We would strongly urge, therefore, that grounds of all kind, whether along the track or the negative bus, be altogether eliminated in every case.

8. UNINSULATED NEGATIVE FEEDERS

A typical form of uninsulated negative feeder system is shown in Fig. 28. It will be seen that this consists essentially in running feeders out from the negative bus to various points of the track. Each feeder may be connected to the tracks at a number of points, and the tracks nearest the power house are connected directly to the negative bus through low-resistance cables. The return cables are therefore directly in parallel with the rails, and the current divides between the rails and the feeders inversely as the resist-

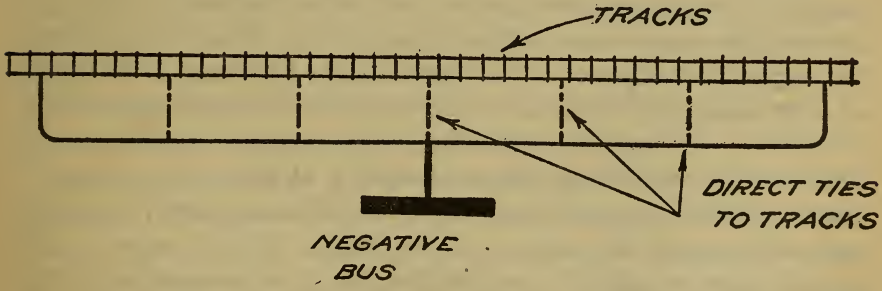

FIG. 28.—*Diagrammatic representation of uninsulated negative feeders*

ance of the various paths. In so far as the principle of operation is concerned it will be evident that it is of secondary importance whether the feeders are actually provided with insulation or not. The fact that they are connected directly to the tracks at both ends, and in some cases at intermediate points, also makes them essentially the same in principle as uninsulated feeders, and they are here so classed whether they are actually laid in the ground bare, provided with insulation, or run on poles overhead. The only effect of insulation on the underground feeders connected in parallel with the tracks would be to reduce slightly the leakage resistance between tracks and ground.

It is obvious that when copper cables are connected in this way potential gradients on the cables will always be the same as that on the rails in the section in parallel therewith. It is shown in another part of this paper that under average conditions in this country good electrolysis conditions require that the all-day average potential gradient in the tracks should in general not exceed 0.3 to 0.5 volt per thousand feet with correspondingly higher values for peak-load periods. These gradients on copper cables would correspond to from 27 to 45 amperes per million circular mils. It is well recognized, however, that the most economical all-day average current density for railway feeders lies between 200 and 300 amperes per million circular mils. The most economical current density would therefore usually be found to be seven or eight times the maximum value required for good electrolysis conditions. It is evident, therefore, that to secure sufficiently low gradients by reinforcing the conductivity of the rails by simply putting cables in parallel with them would be extremely wasteful and not worthy of serious consideration. Hence, some other method must be used if a reasonable degree of economy is to be attained. Such economy is afforded in a large degree by the insulated negative feeder system described below.

9. INSULATED NEGATIVE FEEDERS WITHOUT BOOSTERS

(*a*) *Development of the Insulated Negative Feeder System.*—The use of insulated negative feeders for the purpose of securing low potential drops in the negative return independently of the drop in the feeders themselves has until recently received but little attention in this country, although the principle of their operation and their advantages were pointed out many years ago. The first to suggest the use of insulated feeders instead of uninsulated feeders for electrolysis mitigation was Isaiah H. Farnham, who published an article in Cassier's Magazine in August, 1895. In this paper the fundamental principles of the insulated return feeder system without boosters were clearly set forth, and in view of the more recent developments in this direction it seems remarkable that Farnham's paper did not attract more attention at the time of its publication. This paper is of such fundamental character and reveals such a clear understanding on the part of the author of the principles of the insulated feeder system that we reproduce a large portion of it in the appendix of this paper.

Some years after the appearance of the paper above referred to, a paper was presented before the Institution of Electrical Engineers in Great Britain by A. P. Trotter, in which the principles of the insulated feeder system were set forth in a very able manner, and soon thereafter insulated feeders became widely used in various cities in Great Britain, and at a later date on the Continent, although for the most part they were used in connection with negative boosters.

In this country practically no progress was made for a good many years toward the utilization of the advantages of insulated negative feeders, attention having been almost entirely directed to the application of other methods of mitigation, chiefly those applicable to underground pipe and cable systems.

About 10 years ago a system embodying in some degree the principles of the insulated feeder system was installed in Richmond, Va., and is still in successful operation. In 1907 a paper by George I. Rhodes before the American Institute of Electrical Engineers called attention again to the advantages of insulated feeders for reducing potential gradients in the railway negative return. However, with the exception of the system above mentioned, installed in Richmond, and a similar system installed on portions of the Interborough Rapid Transit Co.'s lines in New York City, practically no progress was made in the direction of the practical application of this system until within the last two or three years. About two years ago the American Railways Co., of Philadelphia, installed a system of this kind on its Springfield (Ohio) property, and has since installed similar systems on a number of their other properties.

A short time afterwards a similar system was installed by the United Railways Co. of St. Louis at its Ann Avenue substation. These two systems in Springfield, Ohio, and St. Louis, Mo., have been given wide publicity, and during the last two or three years many systems of a similar character have been installed in various cities throughout the country. The progressive attitude adopted by the American Railways Co. has done much to call attention to the advantages of the insulated feeder system and to popularize its use, and it is due largely to the important work of this company that the advantages of the insulated negative feeder system are rapidly becoming appreciated by railway companies throughout the country.

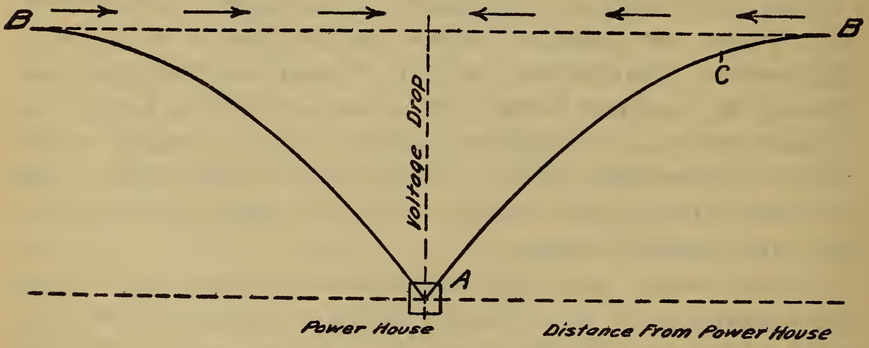

Fig. 29

(*b*) *Types of Insulated Negative Feeders.*—In the insulated negative feeder system, instead of tying the tracks directly to the negative bus and depending on the tracks and such copper as may be in parallel therewith to return the current to the power house, the connection at the power house is either removed or given a suitable resistance, and insulated feeders are run from the negative bus to various points on the tracks, as shown diagramatically in Fig. 30. By this means several important results may be achieved. In the first place, the current being taken off the rails at numerous points, high current densities, and consequently high potential gradients in the rails, can be avoided to any desired degree. In the second place, by so designing the system that the drop of potential on all of the feeders is the same, the current flow in the tracks can be so subdivided that the direction of the flow will be reversed, thus preventing the accumulation of large potential differences between points on the tracks which are some distance apart.

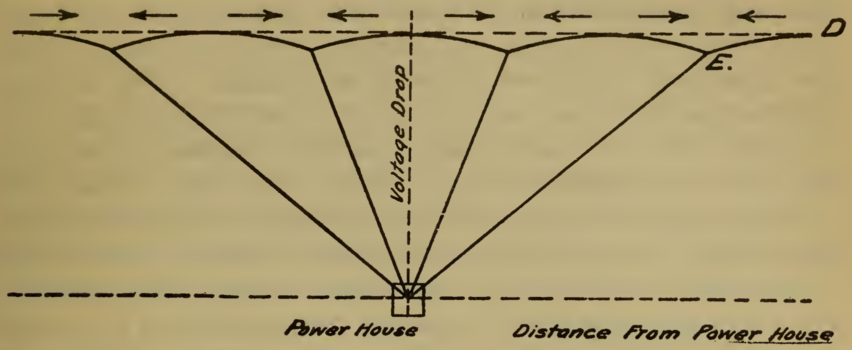

FIG. 30

Further, it will be evident that in this case the actual drop of potential in the different feeders is of little importance so far as electrolysis protection is concerned, so long as it is nearly the same in all. We can thus impose any desired potential restriction on the track and still be free to design the feeders to give maximum economy, which we can not do when the feeders are connected in parallel with the tracks, as has been the common practice in the past in practically every American city. A graphic representation of what can be accomplished by using a system of insulated feeders of this sort is shown in Figs. 29, 30, and 31.

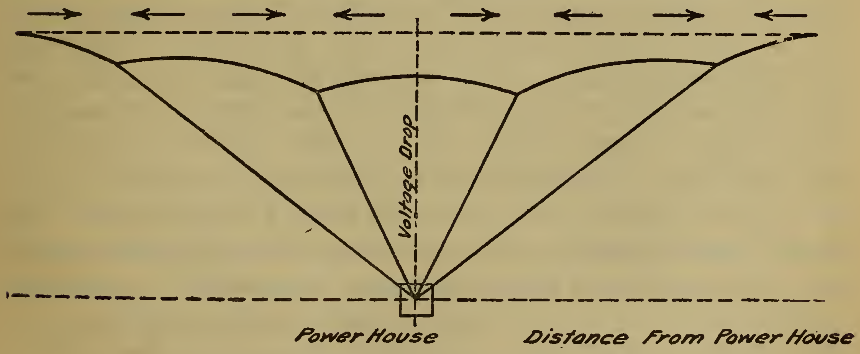

FIG. 31.—*Effect of insulated feeders in reducing rail gradients*

Fig. 29 shows the arrangement of the negative return in which any feeders that are used are connected directly in parallel with the track throughout, and a uniform distribution of the load on the line is assumed. The arrows show the direction of the current flow, and the curved line *AB* shows how the potentials of the rails vary from point to point, the potential curve becoming steeper and steeper as the power house is approached. With uniform distribution of the load, as here assumed, and uniform track conductivity it can be readily shown that this potential curve is the segment of a parabola. Fig. 30 shows the same system with insulated negative feeders run from the negative bus to four points on the track, two in either direction, and so designed that the drop of potential is the same on all during average load conditions. Here also the curved lines represent the potential of the tracks from point to point, and, as in Fig. 29, the curves are segments of parabolas. The portion *DE* of Fig. 30 corresponds exactly to the portion *BC* of Fig. 29. It is seen that the current flow in the tracks is here so subdivided that the total over-all potentials become very small, and consequently the tendency to set up large differences of potential between the rails and surrounding structures is practically eliminated.

An examination of Figs. 29 and 30 shows that the maximum potential difference in the rails is reduced to one-sixteenth of its former value by the installation of only two negative feeders on each side of the station. It is evident, of course, that this great reduction in the potential difference in the tracks is obtained at the sacrifice of track conductance, of which little use is made in the latter case. Between these two extremes any desired compromise can be obtained; that is to say, instead of making the drop on all of the feeders the same, we may make the drop on the feeders lower as we approach the power house, thus making a continuous gradient equal to the maximum allowable gradient all the way to the station. We can thus utilize the conductance of the tracks to the limiting extent consistent with satisfactory electrolysis conditions. This will result in a more economical installation but at the expense of greater over-all potential differences in the track return system, even though the limiting potential gradients in the track may be the same. This type of feeder system is shown diagramatically in Fig. 31.

This latter plan is often more economical than the plan shown in Fig. 30, and it is sometimes to be recommended where conditions are such that there is a large track conductance to be availed of. Wherever the track conductance is small, however, so that most of the current will have to be returned by the feeders anyway, the equal-drop system is to be preferred, since electrolysis conditions will be better and the difference in cost not very great. A still further modification of the insulated feeder system will generally be found to be desirable. In this modification, instead of running several independent feeders in one direction from the power house, a single large feeder is run along the line and connected to the tracks at suitable points by means of resistance taps. This system is shown diagrammatically in Fig. 32. It has the advantage of simplicity of line construction, cheaper first cost and maintenance, due to running one large feeder instead of several small ones (where the total feeder area is not great), and it also has the advantage of bringing back a much larger load on the single feeder, which results in a less variable current, and this makes possible a more economical use of the negative copper.

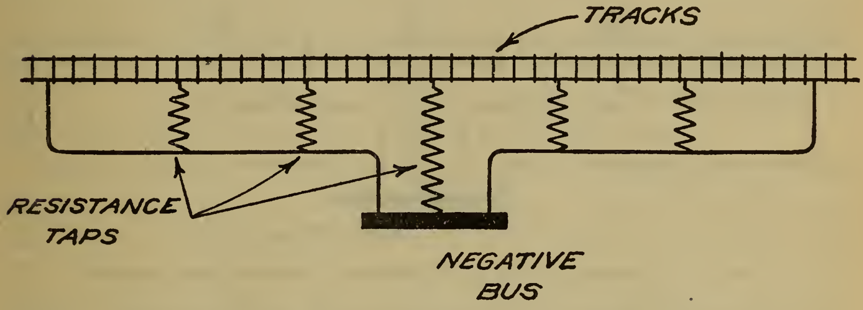

FIG. 32.—*Diagrammatic representation of insulated negative feeders*

From the foregoing it will be apparent that the economy of using insulated negative feeders as compared with uninsulated feeders in parallel with the tracks is so great, particularly when it is necessary to maintain the voltage drops in the track at very low figures, such as is usually necessary for electrolysis protection, that only insulated negative feeders can be considered seriously, and they should always be installed in lieu of uninsulated feeders when the conductance of the tracks is not in itself sufficient to carry the current without excessive voltage drop.

(*c*) *Calculation of Insulated Negative Feeder System.*—It is desirable to state briefly here the methods of procedure in laying out the design of insulated negative feeder systems. A careful study is first made of the load distribution over the entire territory supplied by the station under consideration, and from this study the most natural points for taking off the current are selected and the number of amperes that must be taken off at each point in order that the current in the rails shall not exceed a predetermined value is determined.

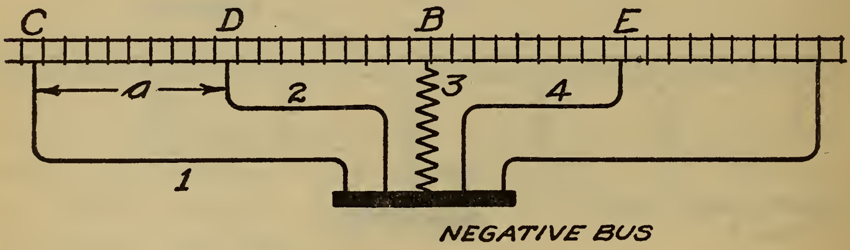

FIG. 33.—*Diagram illustrating calculations of insulated negative feeders*

A preliminary value of potential drop in the first feeder, which is usually one of the largest and most important ones, is then assumed, and from this drop and the current to be carried by the feeder, together with its length, the cross section of the feeder is calculated. When this is done, all of the other feeders must be designed consistently with this so as to avoid potential gradients in the tracks greater than the value determined upon as the limiting allowable average gradient.

Beginning thus with feeder No. 1, Fig. 33, we find that the voltage drop to be allowed on feeder No. 2 is the drop on No. 1 less the allowable drop on the tracks over the distance (*a*) between the points at which the two feeders connect to the rails. For instance, if the assumed drop on feeder No. 1 is 15 volts and the distance between the two taps is, say, 1200 feet and we are permitting a maximum drop of one-half volt per 1000 feet in the tracks, the average gradient between *C* and *D* will in general be less than this figure, depending upon the amount of load originating between these points. The average value of this can be determined from the car schedule. Assuming it to be 0.4 volt per thousand feet, for example, the total average drop between C and *D* will be 0.48 volt. The total drop on feeder No. 2 will therefore be 15—0.48 = 14.52 volts. From this value and the current assigned to feeder No. 2 its cross section can be calculated, the length of course, being already fixed.

We proceed in a precisely similar manner to calculate any other feeders on this same line between feeder No. 2 and the power house, including the resistance tap *B* at the power house. It is then necessary to work outward from the power house in calculating the remaining feeders. For example, if the voltage drop on the power house tap has been found by the above-described procedure to be 12 volts, the drop on feeder No. 4 will be 12 volts plus the allowable drop on the tracks between the power house tap and the point *E* at which the feeder is connected to the tracks, and so on for other feeders more remote from the power house.

Sometimes the cross section of the feeders as thus calculated will be too small to carry the required current without overheating, and when this is the case the feeder must be made sufficiently large to carry the current and an additional resistance inserted preferably at or near the power house in order to give the necessary voltage drop. When this calculation is complete for all the feeders, we are ready to determine whether the original assumption made in regard to the voltage drop on the first feeder was the one that would give approximately the most economical installation over the entire system. To determine this we sum up the total cost of the feeders installed and determine the proper annual charge, including interest, taxes, and depreciation, and also calculate the total annual value of the energy lost in the feeders and resistance taps. If these are approximately equal, the voltage drop assumed was the proper one. If, however, the annual charge on the feeder system is less than the cost of lost energy, the voltage assumed is too high (and vice versa) and a correction must be made.

This correction may be very easily and simply supplied without recalculating the feeder system as in the first instance. For example, if the annual cost of the feeders is found to exceed that of the energy lost by 20 per cent, we must increase the voltage drop by approximately 10 per cent, and reduce the area of the feeders by about 10 per cent, which change will bring the cost to approximate equality, a condition for the most economical installation. If E_1 is the original voltage drop calculated for any given feeder and E_2 is the weighted mean voltage drop for all feeders, then the increase of voltage on any feeder being $\frac{E_2}{10}$ we must reduce the cross section of the feeder by the factor $\frac{E_1}{E_1+\frac{E_2}{10}}$. The value of E_1 in each case is the initial voltage drop calculated for that particular feeder, so that each feeder is corrected by a different factor. When the correction is made in this way there is no change in the potential gradients and current distribution assumed for the rails.

(*d*) *Effect of Concentrated Loads on Effectiveness of Insulated Feeders.*—The view has been taken by some engineers that while the insulated negative feeder system works out very well when applied to a fairly well distributed load it fails to show any appreciable advantage when applied to conditions where the load is concentrated at a few points, such as is usually the case on an infrequent schedule. While this is true when we consider the maximum values of potential drop between different points of the negative return, it is not true if we are considering the effectiveness of the electrolysis protection afforded. The significance of this statement will be made more clear by reference to Fig. 34.

Let us assume, as shown diagramatically in Fig. 34, that we have a linear railway system to which a number of insulated feeders are connected at distributed points, the feeders being so designed that the resistances of all of the feeders are substantially the same. Let us assume also that we have a single train operating on the line in which case the load will be delivered to the tracks at one point which will be moving back and forth on the line. Consider first the conditions that prevail when the car is at the point A. It will be evident that the current delivered to the rails will divide at the point A, a portion of it going over feeder No. 1 and the remainder going in the direction of B, as shown by the arrows.

Since the current going in the direction of *B* will find several parallel paths by which to return to the negative bus, each path having approximately the same resistance as path No. 1, it will be evident that in this position of the train the greater part of the current will remain on the tracks between *A* and *B*, the track current being reduced somewhat at *B* and again at *C* and also at *D*, and finally the remainder going off on feeder No. 5 at *E*. Under these conditions the drop of potential in the tracks will be continuous from *A* to *E*, the point *A* being that of highest and point *E* that of lowest potential. Under these conditions the leakage currents tend to leave the track in the region of *A* and *B* and return to the track again in the region of *D* and *E*. The general direction of this leakage current is shown by the curved dotted lines and attached arrows.

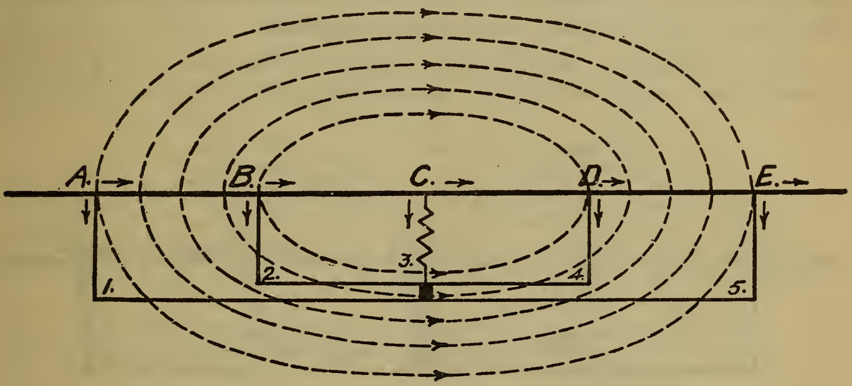

Fig. 34.—*Reversal of leakage current with concentrated load and insulated negative feeders*

Since only a small part of the current is taken off on the insulated feeder at *A*, it is evident that if this condition were to be permanent electrolysis conditions would be nearly as bad as if feeder No. 1 did not exist. However, the load which was originally at *A* progresses along the track in the direction of *E*, and when it arrives at *C* it is evident that this is the point of highest potential, and in this position part of the current is going off over feeder No. 3, part of it is flowing on toward *D*, and a portion flowing back toward *B* and going on feeders Nos. 1 and 2.

The direction of current flow under these conditions is shown by the arrows in Fig. 35, and the leakage currents, as shown by the curved lines, tend to flow off in the region around *C* and enter the tracks again at the ends of the line in the vicinities of *A* and *E*. It will thus be seen that the direction of the potential gradient in the section between *A* and *C* has become reversed. Thus, as the load progresses in the direction of *E* the direction of the current flow in the tracks to the left of the load will always be the reverse of what it was in the beginning, and finally when the load reaches the point *E* the voltage conditions of the entire line are exactly the reverse of what they were in the beginning.

The conditions at this time are shown in Fig. 36. The point *E* is now the point of highest potential and *A* is the point of lowest potential, and the leakage currents tend to leave the tracks in the regions around *A* and *B*. It will be evident, therefore, that if there is a pipe system paralleling the railway line, and the load is concentrated at *A*, the pipes in this vicinity will be negative to the tracks, and a certain amount of corrosion will take place at the latter point. When the load is shifted to *E*, however, the pipes become negative to the tracks in the vicinity of *E* and positive around *A*. It will therefore be evident that as the concentrated load moves back and forth along the line it gives rise to cyclical variations in the potential difference between the pipes and tracks at any given point, the pipes becoming alternately positive and negative as the load is remote from or near to the point under consideration. This fact is of very great importance in determining the magnitude of electrolysis damage that will result.

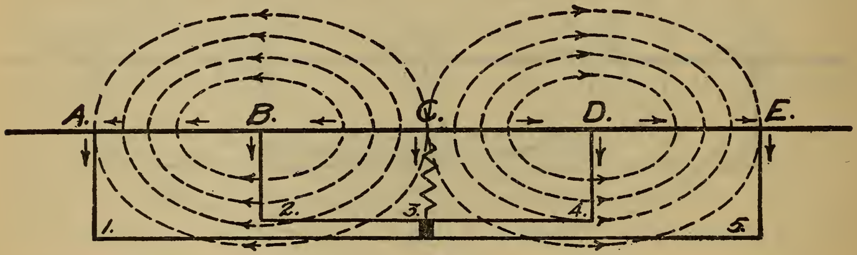

FIG. 35

Extensive experments have shown that the process of electrolytic corrosion of iron when embedded in the soil is to a limited extent a reversible process. During any interval when the iron is discharging a current into the earth the iron will be corroded and go into solution. If conditions are such that the iron remains in solution near the surface of the pipe until the direction of the current is reversed, there will be a tendency for the metallic iron to be plated back on the pipe. This will usually be deposited in a more or less spongy form that will have no value mechanically, but it is nevertheless in the form of metallic iron in contact with the outer surface of the pipe, and when the iron again becomes positive this same iron must again be corroded before the deeper layers can be affected.

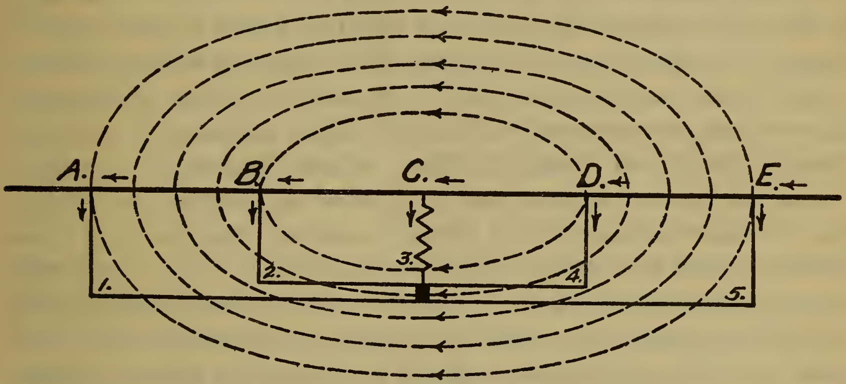

FIG. 36

If this process were entirely reversible, an alternating current would do no damage at all in the way of corrosion, but unfortunately the process is not entirely reversible. Oxygen dissolved by the soil waters coming in contact with the dissolved iron salt tends to precipitate the insoluble iron oxides, and when this occurs the iron can not entirely be plated back on the pipe upon the reversal of the current flow. For this reason an alternating current will produce a certain amount of electrolytic action, and the slower the frequency of the reversal the more oxidation of the dissolved iron will take place and consequently the greater the amount of the corrosion.

Experiments have shown however, that if the period of the cycle is made quite long, as much as 10 to 15 minutes, or even longer, the actual amount of corrosion that occurs, while it may be very considerable, is nevertheless very much less than would be the case if voltages of the same magnitude existed in the negative return and always in the same general direction. For this reason this negative feeder system, when used in connection with a concentrated load, will always give much greater reduction in the actual amount of the electrolysis damage than it does in the actual voltages which exist from time to time between different points in the negative return. In consequence of this fact, it may be stated that so long as improvement in electrolysis conditions is the object sought, the insulated negative feeder system may be regarded as being quite as applicable to a system having concentrated loads moving back and forth along the line at frequent intervals as to a system in which the loads are more or less uniformly distributed along the line. When, however, the period of the load cycle becomes half an hour or an hour or even longer the corrosion becomes much greater, and may then become quite serious unless the voltages are kept very low. To be sure, the energy loss can be shown to be greater with the concentrated load than with a distributed load, but this is true exactly in the same ratio on both positive and negative feeders and in the uninsulated rail return; and this fact can not, therefore, be considered in any sense whatever a defect in the insulated negative return feeder system when applied to loads of this character.

10. INSULATED NEGATIVE FEEDERS WITH BOOSTERS

(*a*) *Direct Boosters.*—The insulated negative feeder system described above, because of its simplicity and economy will be found most suitable for practically all cases where the feeding distances are not too great. Cases are frequently encountered, however, in which one or more of the lines are supplied over such a great distance that serious difficulites are encountered. For instance, if the power house is supplying a network of lines near the station, insulated feeders may be made to take care of this area without requiring a voltage drop on the feeders or the power-house tap of more than perhaps 10 to 20 volts. At the same time one or more very long and perhaps heavily loaded lines may extend from the network, and if an insulated feeder, as above described, is to be used to take care of this line also, it would be necessary to use a very heavy feeder in order to keep the voltage drop comparable with that on the feeders running to the local network, or else a high resistance would have to be inserted in series with the latter.

The former alternative would involve a prohibitive charge for copper, while the latter, by making all of the current from the network return over a relatively large voltage drop in the power-house tap, would give rise to large power losses. These difficulties can be avoided by designing both the local feeder system and the long line on the basis of the most economical size of cables and connecting in series with the long line a booster designed to supply the voltage necessary to force the required currents over the long feeder. This booster will consist of a direct-current generator of suitable voltage to take care of the peak-load drop of the feeder, coupled to either a 600-volt D. C. motor or an induction motor, according to circumstances. By the use of such a booster it will sometimes be possible to save enough in copper investment or power losses to more than compensate for the losses in the booster and the installation cost and complication which attend its use. Such a booster system is shown diagramatically in Fig. 37, and this arrangement is called a direct-booster system.

(*b*) *Inverted Boosters*.—Instead of connecting a direct booster in series with the long feeder, as above described, a similar result can be accomplished by insertion in series with the shorter feeders supplying the local network an "inverted" booster. This would consist of a series-wound motor connected in series with the local feeder system, this motor being used to drive a constant-speed generator connected to either the D. C. or A. C. bus bars. If the latter, an induction generator would be preferred. With this arrangement the speed would be held substantially constant, and hence the counter emf of the series motor would be proportional to the current, which condition would be necessary for maintaining the proper balance between the two feeder systems. Such a system is shown diagrammatically in Fig. 38. A little consideration will show that when such an inverted booster is used in lieu of a resistance tap, instead of the energy being dissipated in the resistance tap the excess energy over that required to supply the booster losses is delivered back to the D. C. or A. C. bus bars through the generator driven by the series motor.

It is evident that the operating characteristics obtained from these two booster systems will in general be substantially the same. The choice between them will therefore depend mainly on the relative load in the two parts of the system. It is evident that if the greater part of the load is on the long feeder, the use of a direct booster in this feeder would require a larger and more expensive machine as well as greater power losses in the machine itself than if the inverted booster were used in series with the relatively small load in the local network. Hence, if the load in the local network is the smaller an inverted booster would be cheaper, while if the greater part of the load originates in the local

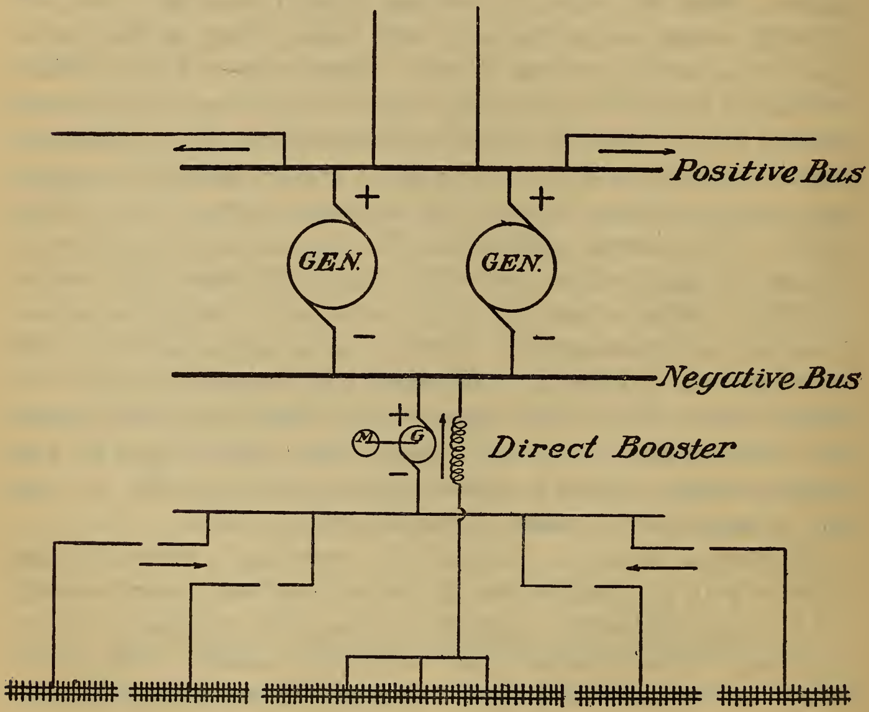

Fig. 37.—*Direct booster system*

system a direct booster in the long feeder would be indicated. In the majority of cases, however, the insulated feeder system without boosters as described in the preceding section is found to be as cheap or cheaper than either of the booster systems, and is generally to be preferred because of its greater simplicity.

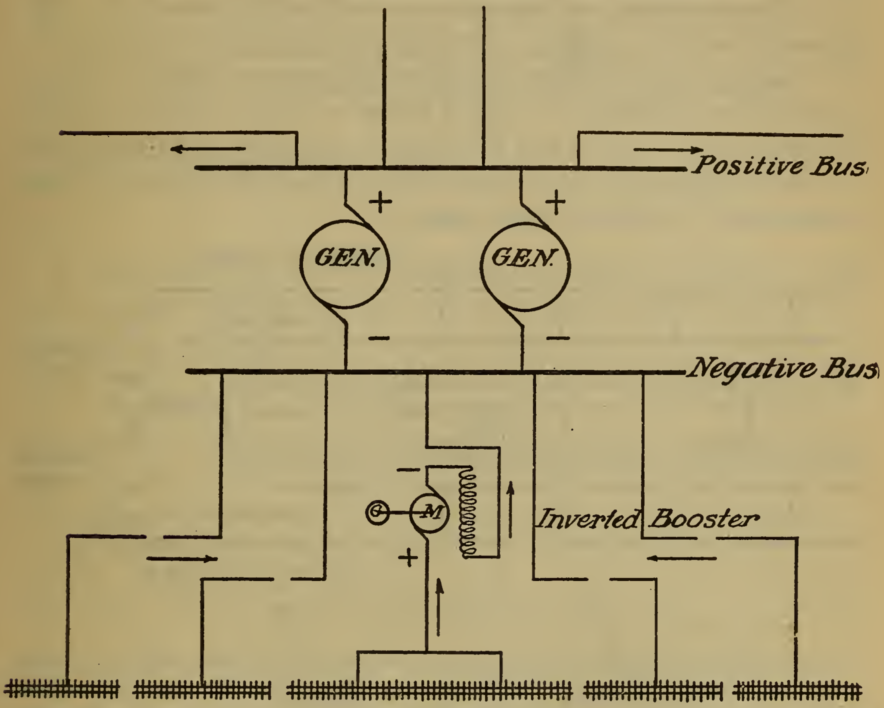

FIG. 38.—*Inverted booster system*

11. THREE-WIRE SYSTEMS

A method that has received some consideration for railway work, partly as a means of securing greater economy in the distribution of power and partly as a means of reducing electrolysis troubles is the three-wire system using the tracks as neutral. By this means the current flow in the rails could in general be greatly reduced, but the practical value of this method under average conditions remains yet to be demonstrated. Aside from the cost of converting to this system which would in any case be considerable and in many cases prohibitive, there are certain operating disadvantages, such as greater variations in the car voltage, resulting in less satisfactory car operation and inferior car lighting.

There is also the condition that one-half of the trolley wire network will be at a high difference of potential against the other half, and in one form of the three-wire system this increases the cost of construction and maintenance and the difficulty and danger of making repairs. In many cases, also, where single-track lines run on separate streets, with a long distance between track crossings, it would be necessary to install either a double trolley on each street or to run heavy and expensive cross bonds from one street to another in order to prevent large potential differences from developing between the two tracks.

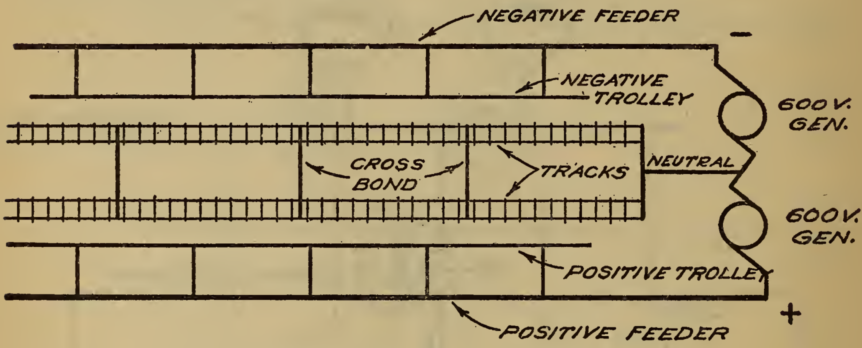

FIG. 39.—*Parallel three-wire system*

(*a*) *Parallel Three-Wire System.*—The three-wire system may take two different forms the same in principle but differing radically as to the arrangement of the feeder system. One of these is directly analogous to the ordinary three-wire system of lighting and is called the parallel three-wire system. The typical arrangement for the case of a double-track line using this system is shown in Fig. 39. Here one trolley is negative and the other positive, the tracks being neutral. It is evident that only the difference in the load on the two sides of the line returns to the power house on the track, although there may at times be heavy circulating currents flowing between cars in short sections of track. If the cars run at frequent intervals, however, such circulating currents will not have to flow over sufficiently great distances in the tracks to set up nearly as large potential differences therein as would exist with the same loads under the ordinary track-return system. The result would be that where load conditions are reasonably favorable for the work of the three-wire system large reductions in potential drops in the negative return could be secured.

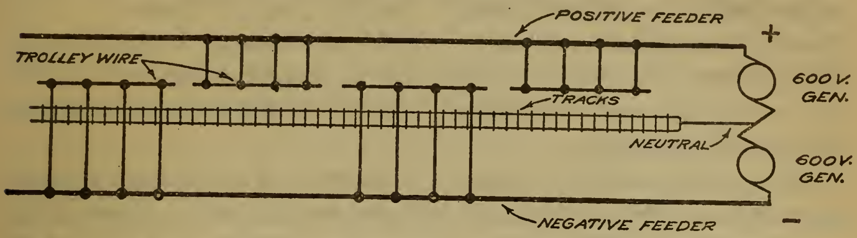

FIG. 40.—*Sectionalized three-wire system*

A single-track line with two overhead trolleys, one positive and one negative, can also be used, or the two tracks may be on different streets, the trolley on one street being positive and that on the other negative. The latter, however, is open to the objection that since the current would generally tend to flow in one direction in the tracks on one street and in the opposite direction on the other, frequent cross-bonding becomes very important, and unless the two lines are close together this would become quite expensive.

(*b*) *Sectionalized Three-Wire System.*—The other form of three-wire system is shown diagramatically in Fig. 40. In this form the feeding district is divided into sections, and alternate sections are supplied by feeders running directly from the positive bus, while the remaining sections are supplied by feeders from the negative bus, the difference of potential between the two busses being 1200 volts. In this way the existence on the same portion of the street of two trolleys having a high difference of potential between them is avoided. The tracks as before serve as the neutral and convey the current from the cars in one section to those in the adjoining section and return the unbalanced current to the power house.

The advantages of this form of three-wire system are (1) that it separates the positive and negative trolley sections, keeping them on different portions of the line, and (2) any system in which the substations have two positive busses and two or more generators can quickly and cheaply change to this system, the only requirement being to sectionalize the feeding and trolley system in such a way as to properly balance the load.

Both of these three-wire systems require for satisfactory operation a fairly well balanced load, and hence they will operate more satisfactorily in sections where the schedule is frequent. For infrequent suburban or interurban service, voltage fluctuations at the cars would be serious, giving rise to unsatisfactory car service and car lighting and undoubtedly increasing the maintenance cost of the car equipment.

The system would also require a number of generators in each substation or their equivalent in three-wire generators, which have not as yet been built for 600-volt service. On the other hand, it would, if properly arranged and operated, unquestionably greatly reduce the average potential drops in the tracks. It would have the further advantage that the shifting of the car loads would frequently reverse the polarity of the leakage currents, and this tends still further toward reducing electrolysis damage for reasons explained above under the discussion of insulated return feeders.

As pointed out at the beginning of this section the three-wire system has sometimes been considered as a means of increasing the economy of power distribution. While it does accomplish something in this direction, it does not possess the advantage that is at times claimed for it. A little consideration will show that a perfectly balanced three-wire system operating with 600 volts on each side is identical with a 1200-volt, double-trolley system in so far as the amount of feeder copper required is concerned. Since in any double-trolley system the amount of copper required on the return portion of the circuit would be in general equal to that on the outgoing lines, the total copper for a 1200-volt, double-trolley system would be substantially the same that is required for a positive feeder system of a 600-volt track-return system. It follows, therefore, that a three-wire system requires the same amount of copper and the same energy loss in the feeders when we consider both positive and negative sides as is required in the positive-feeder system of the ordinary 600-volt network.

The only economy resulting from the installation of the three-wire system, therefore, is the saving in track losses, which are greatly reduced, although not entirely eliminated. Track losses, however, are generally much smaller than the losses in the positive-feeder systems, so that the economy in this feature, while important in some cases, would be very small compared with the economy that would result from doubling the voltage on the ordinary track-return system. The relatively small saving in the track losses would, however, be largely offset, if not more than counterbalanced, by the increased station costs due to the more expensive and less efficient units required.

Judged solely from the standpoint of electrolysis protection the three-wire system must be said to possess considerable merit, and its adoption along with proper precautions regarding load balance, track bonding, and cross bonding, would undoubtedly take care of the electrolysis problem in a very effective manner. Thorough tests of these systems under conditions to which they are best adapted would be very valuable. As yet, however, so little experience has been had with the operation of these systems that it is not possible to say how satisfactory this would prove under average conditions from the operating standpoint. A sectionalized three-wire system has been in operation in Nurnberg, Germany, for 12 years, and appears to be giving satisfactory service. Experiments have been made with the system in this country, but it was abandoned because of operating difficulties encountered. At the present time, so far as we are aware, only one three-wire system is being experimented with in America. This is a sectionalized system in operation on a portion of the lines of the Pacific Electric Railway Co. in Los Angeles, Cal. It has only recently been installed, and its success has not yet been determined.

12. NUMBER AND LOCATION OF POWER HOUSES AND SUBSTATIONS

In a general way the effect of the number of feeding points on the potential drops in the rails and the consequent leakage of current from the tracks is obvious, but some of the more important aspects of this problem are obscure and often not appreciated. The economic aspect of the question is also more complex than is generally recognized. In the broadest terms we may consider the matter under two heads, namely, (1) the effect of the number and location of the stations on the tendency of the pipe systems to pick up stray currents from the return, and (2) the effect on the total drop of potential on both sides of the line.

As to the first of these we have to consider the fact that as the number of stations is reduced the capacity of each must be increased, with the result that the current flow in the rails approaching the power house will be greater and the increased potential gradients resulting therefrom cause correspondingly increased leakage of current from the tracks. Further, as the distance between stations is increased the tendency of pipe lines to take up current from the earth under a given potential gradient increases much more rapidly than the distance of transmission. In fact, it can be shown that the current picked up by the pipes may increase either as the second, the third, or even a higher power of the distance between feeding points, according to the character of the system under consideration. Any increase in the number of feeding points, or, more properly speaking, the number of "drainage points" or points at which current is taken from the track, will reduce in much greater degree the flow of stray currents in the pipes.

The number of drainage points can be increased to any desired extent by the proper use of insulated negative feeders, as above described, but the fewer the stations the longer and heavier the feeders must be, and in consequence of this an increase in the number of stations may often prove to be in the interest of economy, considering only the negative return. This economy will become much more pronounced when we consider also the distribution of the power on the positive side as well as its return on the negative.

When we come to consider the question of total drop of potential in the distribution and return of the current we have many complex factors to consider. One of these factors is the loss of power resulting from such drop of potential, but the calculation of the value of this lost power is by no means so simple as might at first appear. It is not sufficient simply to determine the total energy loss during any given time and multiply this by the cost of power per kilowatt hour in order to determine its value. We must consider that the loss of power is proportional to the square of the load and hence is greatest at time of peak load when the capacity of the power station is usually taxed to its utmost. The capacity of the generating plant and hence the fixed charges on the cost of power are thereby increased; or if the power be purchased, there is usually a fixed charge imposed on the maximum demand. In any case if the operation of the system is such that the line losses give rise to an increased demand for power at time of peak load, the cost of the lost power will be greater than the cost of the power utilized at the cars.

Besides the question of lost power due to line drop we have to consider also the effect of this drop of potential on the character of the car service and the cost of operation of the car system. Low voltage means lower average car speed, with a consequent increase in the number of cars required to operate at a given headway, which in turn increases both fixed charges and operating costs. Any change in the distribution system, therefore, whether a change in the number of stations or any other change which affects materially the line losses, will exert a marked effect on the cost of operation of the system. In designing a system of electrolysis mitigation, therefore, many things have to be taken into account quite apart from the technical points regarding the electrical condition of the negative return, if a proper balance is to be maintained between the cost of making the proposed changes and the benefits resulting therefrom.

In considering the installation of a new system of electric power distribution for street railways complete, without regard to existing power stations, it would be a comparatively simple matter from a detailed study of the system in question to determine the proper number of stations and the best location of the same in order that best results might be secured, all things considered. But even if such a system were installed which answered in an ideal manner the requirements of present-day service, it would be but a few years until the growth of traffic and shifting of business centers would require increases in the size of the plants and other changes which would make the system much less economical than the ideal.

In studying a system already installed we may be able to show that the feeding distances for some or all of the various stations are too great for economy and that a greater number of stations with reduced feeding distances would provide a much more economical system of distribution. It does not follow, however, that an increase in the number of stations in such a system will actually improve its economy, but on the contrary the reverse might be the case, for, although the present feeding distances may be considerably too great for maximum economy, the location of the stations with respect to each other may be such that the placing of a new station in between will overstep the point of most economical feeding distance and even raise the net cost of operation, whereas the cost of moving old stations to more desirable locations might be altogether prohibitive.

In dealing with existing conditions, therefore, we must work under considerable restriction, and many things must be taken into account before it can be determined definitely whether or not a proposed substation will prove desirable from an engineering and economic standpoint.

13. SUMMARY OF METHODS OF MITIGATION

In the foregoing review of the various methods that have been proposed for reducing troubles from electrolysis those treated in the first section relate solely to protective measures to be applied to the pipes. Of these the first seven are found to be of little value for extensive application to networks of any considerable size, and certain of them are shown to be actually detrimental because of their tendency to accelerate deterioration of the pipes. The method of insulating joints, and a properly designed pipe-drainage system are of practical value, but it is recommended that their use be restricted to auxiliary measures used in connection with certain of the measures described in the second section for application to the track-return system. This recommendation is made for two reasons—first, because the practical working out of these systems applied to the pipes usually places an undue part of the burden of mitigation on the pipe-owning companies, and second, because the adequate protection of all subsurface structures by either of these means in cities where potential gradients are allowed to remain high will in general prove a difficult and expensive matter.

A more logical, and at the same time a more effective and often more economical, procedure is to attack the source of the trouble by eliminating in a large measure the leakage of the electric currents into the earth. Numerous methods applicable to the railway return system are available for this purpose, but, as pointed out in the foregoing review, the majority of these, namely, the alternating-current system, the double-trolley system, the use of negative trolley, the periodic reversal of trolley polarity, and the use of uninsulated negative feeders in parallel with the rails, when considered solely as methods of electrolysis mitigation, are either impracticable or else open to the objection that the expense or operating difficulties attending their application are rendered unnecessary because of the fact that there are other adequate methods available for general application which are comparatively cheap to install and which introduce but slight complications into the operation of the system.

The importance of proper construction and maintenance of track return is emphasized. Thorough bonding and cross bonding are urged, and it is pointed out that at times it may be desirable on the ground of economy to use somewhat heavier rails than would be called for solely by traffic conditions. The drainage of roadbed where practicable is also urged, and where track is laid on private right of way the rails and ties should be kept, as far as possible, out of direct contact with the earth in order to reduce leakage of the current to a minimum. Good well-drained rock ballast is very effective for this purpose.

It is also pointed out in the foregoing that a three-wire system, when viewed solely from the standpoint of electrolysis mitigation, possesses large possibilities, and experiments with these systems under favorable conditions are urged. Attention is called to the fact, however, that up to the present time sufficient experience has not been had with these systems to show whether they are practicable from the operating standpoint under average conditions of service. At the present time it must be regarded as an experimental system which may under favorable circumstances be found of value in relieving electrolysis troubles.

The most effective methods that have been thoroughly tried out in practice over long periods are the use of insulated negative feeders, either with or without boosters, as described above. It is pointed out that in most cases where the feeding distances are not too long an insulated feeder system without boosters will prove cheapest and at the same time more satisfactory because of its greater simplicity. It is possible by the proper application of either of these insulated feeder systems to reduce the potential gradients in the earth to such low values that in most cases little damage would result, and they can consequently be made very effective in relieving electrolysis trouble.

In many cases, however, it may be better where conditions are favorable to combine one of these methods with either the insertion of a moderate number of insulating joints in the pipes or with the use of a very limited amount of pipe drainage, providing conditions are favorable to its use. The insulated-feeder system would be applied to reduce the potential gradients throughout the system to very low values and one or the other of the auxiliary systems used to eliminate largely any residual electrolysis that might still remain.

By the proper use of the measures set forth above it is in most cases possible to secure sufficiently low-voltage drops in the negative return to afford adequate protection to underground pipes, so that there will be little need for resorting to the use of any auxiliary measures, such as pipe drainage or insulated joints in the pipes. In fact, it has frequently been found that a careful study of the power distribution system, such as should always be made in connection with the design of an electrolysis mitigative system, will show that changes in the distribution system could be made that would yield operating economies which quite apart from any considerations of electrolysis protection are more than sufficient to justify the expense involved. We have found this to be true in so many cases that we are convinced that the adoption by the railway companies of the best measures for reducing voltage drops to such low values as substantially to eliminate electrolysis trouble would in very few cases result in financial hardship.

V. REGULATIONS REGARDING ELECTROLYSIS MITIGATION

1. NEED FOR REGULATIONS

The many conflicting interests involved in the electrolysis problem make it imperative that some sort of regulations governing the procedure of the various parties in interest be adopted if a permanent and just settlement of the problem is to be secured. It is true that conditions vary greatly in different localities, and always to attain a complete solution would require a separate investigation for each case. In general, however, it is not practicable to make a detailed engineering investigation of each locality, such as would be necessary in order to prescribe regulations especially adapted thereto. As in all other cases where diverse interests come into conflict the interests of all will be best safeguarded by the adoption by a proper authority of more or less specific regulations defining the responsibilities, rights, and limitations of the parties to the dispute.

In the case of electrolysis, long experience both in America and abroad has shown that some sort of regulations are necessary for protecting underground pipes and cables and that such regulations can be made very effective. To be sure, any set of regulations drawn to meet average conditions might in special cases fail to give sufficient protection, and in other cases might cause somewhat greater expense than would be necessary if each case could be considered in detail by itself. Such regulations would, however, insure fair and adequate treatment of all parties concerned under general average conditions, which would be a great improvement upon present practice in most places. Such regulations wisely drawn would not alone protect pipe-owning companies, but would often benefit the railway companies also. In the absence of such regulations a single serious case of trouble traceable to electrolysis such as might occur, or the activity of interested or overenthusiastic individuals, may lead to hasty and ill-considered legislation, resulting in rules much more drastic than conditions call for, and lead either to undue hardship on the railway companies or to long and costly and perhaps fruitless litigation.

Regulations would also define definitely what is expected of the railway companies and enable them to treat the matter as one of the definite engineering problems connected with the operation of the railway system. They could thus plan and build definitely and with the assurance that they would not be continually harassed by agitation of the subject of electrolysis.

2. PROPER AGENTS FOR DRAWING PROPOSED REGULATIONS

It is very important, however, that such regulations should be drawn with the greatest care and with due consideration of the interests both of the railway and the pipe-owning companies. They should not be drawn by persons unfamiliar with requirements, nor by the representatives of any one of the interests concerned, but by all of such interests acting jointly. It is hoped that such joint action may be taken in the near future as a result of the work of the National Joint Committee on Electrolysis now at work on the general subject of electrolysis. The work of that committee is primarily educational and is not concerned at all with the legal aspect of the question. Nevertheless, a careful scientific and engineering study and report will lead at least to a partial definition of the requirements and responsibilities of the various utilities interested in this problem.

3. PRINCIPLES ON WHICH REGULATIONS SHOULD BE BASED

It is not our purpose to present here anything in the way of a set of regulations suitable for enactment into law. We shall, however, discuss briefly the fundamental principles on which we believe such regulations should be based.

The various factors which determine the electrolytic conditions of underground structures, such as overall potentials and potential gradients in the track or pipe network, potential differences between pipes and tracks, and between various pipe and cable systems and the earth, current flow in the pipes, current density of discharge from the surface of pipes, etc., while important in any complete electrolysis survey, are for the most part subject to such a variety of influences that they are not suitable for use as a basis for regulations. The factors selected must not only afford a fair criterion of the general electrolysis situation, but they must at the same time be susceptible of easy measurement, and they must lend themselves to ready and fairly accurate predetermination, so that the railway return system can be designed to meet the regulations with a minimum of uncertainty.

All of the above-mentioned factors except the overall potential measurements, and potential gradients in the track return, are affected to a great extent by the character of the pipe systems, and changes in the latter may produce marked changes in most of the former; and hence these factors are only partially under the control of the railway company. Further, none of these other factors except the potential drops on the pipe systems afford an accurate criterion of the danger from electrolysis. They are therefore unsuitable for use as a basis of specific regulations designed to protect underground structures.

The overall potential and potential gradient measurements, on the other hand, particularly those taken on the pipe systems, afford practically as good a criterion of the danger existing when interpreted in the light of general experience as any other measurable factors. They are fairly definite, readily measurable, and in very large degree under the control of the railway company; hence they are best adapted for use as a basis of rules and regulations.

In all laws and regulations that have up to the present time been adopted, so far as we are aware, the over-all potentials and potential gradients have been specified as those taken between various points on the railway tracks. This is true of the various European ordinances as well as those adopted in this country. These are very good criterions in many respects and have proven successful, particularly in Europe, in relieving electrolysis troubles. There is much to be said, however, in favor of limiting potential drops on the earth or on pipe networks rather than on the railway track. Such voltages afford the most accurate criterion of all, as to the actual danger to the underground structures, and would also prove more advantageous to the railway companies.

If potential drops on the earth or pipes be made the subject of limitation, higher voltages could be allowed in those tracks having a high resistance to earth. This would apply to tracks laid on a well-drained roadbed, for example, and with still greater force to tracks on private right of way where the rails are set up on ties out of contact with the earth. On the other hand, relatively low voltages would have to be maintained in tracks in which the rails are much of the time in intimate contact with moist earth, or otherwise constructed so as to give a comparatively low resistance to ground. Under this plan low voltages in the track would be required only where most needed and the railway company would be encouraged to so construct the tracks as to give a high leakage resistance to ground. It is evident that if the leakage resistance to ground be made high, practically all of the current will be compelled to return to the negative bus by way of the railway negative return and thus increase the voltage drop on the tracks, although reducing electrolysis troubles. If, however, the voltage drop on the tracks is limited by regulations any construction of roadbed that would reduce leakage would increase the difficulty and cost of complying with the regulations. On the other hand, if the voltage drop on the pipes is made the basis of the regulations, the railway companies would profit by any construction which tends to reduce leakage instead of suffering by it, as in the case where voltage drops in the tracks are limited. If this plan were adopted, it would of course be necessary to prescribe lower voltage limits than would be applicable to tracks in order to secure the same freedom from electrolysis.

4. VOLTAGE LIMITS IN TRACKS

(*a*) *Previous Experience Regarding Voltage Limitations.*—In this country little experience has been had until recently with railway installation in which voltage drops in the negative return have been maintained low enough to give substantial freedom from electrolysis trouble. The prevailing practice in a majority of the cities of America has been to permit rather high voltage drops in the return circuit, and it is for this reason mainly that electrolysis troubles have assumed much more serious proportions in this country during the past decade than in almost any other country. There has, therefore, been but little experience in this country that can be used as a reliable guide as to just what voltage limits can be considered safe, although there is abundant and incontrovertible evidence in regard to what voltage limits may, under many circumstances at least, be considered unsafe.

On the other hand, in Great Britain and many parts of continental Europe much experience has been had with installations in which quite low voltages have been maintained over a period of many years; and this long experience has shown that the voltages which have been maintained in these countries are such as to insure, under average conditions, substantial freedom from electrolysis. This experience, therefore, is a valuable guide in determining what voltage limits can be considered safe under similar conditions here.

(*b*) *Voltage Limits Prevailing in Great Britain.*—In Great Britain the maximum allowable voltage drop between any two points of any railway system, near which underground metallic structures are laid, is limited by law to 7 volts. This law has generally been complied with by the railway systems of Great Britain, and where this 7-volt limit has been substantially complied with there has been comparatively little trouble from electrolysis of underground structures.

In some instances this legal limit has been considerably exceeded, due primarily to the fact that the British Board of Trade, which is charged with the responsibility of administering the law, has not made it a practice to make investigations of electrolysis conditions on its own initiative, but only on the complaint of interested parties. For this reason isolated cases can be found in which the prescribed voltage limits are for a time exceeded, and it is doubtless due largely to this fact that most of the electrolysis trouble, that has been experienced in Great Britain, has occurred. On the other hand, in many cities in Great Britain the limits prescribed by the ordinance have not only been met, but the prevailing voltage drops under ordinary traffic conditions have been found to be considerably below the maximum limit prescribed by law.

The accumulated experience with the voltage limits which prevail in Great Britain appears to show quite conclusively that voltages of the order of the magnitude of those maintained in the railway systems there are none too low to assure adequate protection to underground structures; and it is the opinion of some competent engineers that even lower limits are desirable and commercially practicable. This attitude was taken by the engineers who drew the regulations that are now in effect in many cities of continental Europe.

(*c*) *Voltage Limitations in Germany.*—The so-called German regulations, which are in effect in many cities in continental Europe, while differing radically in the manner in which the voltage limits are defined, were designed by the framers of the regulations to yield somewhat lower average voltage conditions than those demanded by the British law. The German regulations prescribe a voltage limit of 2½ volts throughout any city network of street railway lines, and they further prescribe a limit of 1 volt per kilometer (0.3 volt per 1000 feet) on interurban lines. These limits are applied to the period of average scheduled traffic instead of to the peak-load period, as in the case of the British law.

In both of these sets of regulations, the definition of voltage limits is indefinite and unsatisfactory. The British law limits the maximum drop to 7 volts, but does not specify whether it is the momentary maximum that is subject to limitation, or the sustained maximum during some definite interval of time. In applying the law, however, the British Board of Trade has found it necessary to adopt for administrative purposes a more specific definition of the term "maximum voltage." In determining this maximum voltage, the average value for the half hour of highest load is determined, and also the maximum momentary drop during this period, and the mean of these two values is taken as the maximum voltage within the meaning of the law.

In the German regulations a similar ambiguity exists. While it is stated that the voltage under average scheduled traffic should not exceed certain values, it is debatable whether or not it is intended that the momentary value of voltage drop under ordinary schedule traffic is to be kept within the prescribed limit or whether the average value of voltage drop under normal operating conditions is the value to be considered. If we place the latter interpretation on the question, the limit appears to be reasonable and practicable, and one that would, under many circumstances, be applicable in this country. If, however, it is intended to limit the momentary voltage under average load conditions in street railway networks to 2½ volts, the regulation would be altogether too severe for general application, as a voltage limitation of this severity is not needed for providing reasonable protection to underground pipes and the cost of meeting such limitations would be altogether out of proportion to the benefits that would accrue therefrom.

If we assume, then, that this over-all voltage limit of 2½ volts is to be taken as the average value under normal scheduled traffic, it would be found to compare very well, so far as ultimate results are concerned, with the voltage limits in effect in Great Britain. It will be apparent that the maximum value of 7 volts, defined as the mean value between the average for the maximum half hour and the highest momentary value for that hour would correspond to a mean value for the maximum half hour of approximately 4 to 6 volts under most traffic conditions. On a basis of 50 per cent load factor, this would give a mean value under average load conditions of 2 to 3 volts, which is of the same order as the 2½ volts average limit named in the German regulations.

The above discussion relates only to the over-all voltage limits prescribed by the regulations in question. The German regulations make no provision for restricting the potential gradient within the city network proper, the gradient limits of these regulations applying only to interurban lines. The British law, however, contains a provision which limits the current density in any street railway rail to 9 amperes per square inch of cross section. This, in effect, prescribes a potential gradient limit, which, however, is variable according to the resistivity of the rails; and for rails of average resistivity this gradient limit would yield a maximum potential gradient of approximately 0.9 volt per 1000 feet, exclusive of the drop on the joints. This would correspond to an average all-day gradient of from 0.3 to 0.4 volt in the case of most railway loads.

It is very desirable to have both the overall voltage limit and the potential gradient limit, the latter to prevent too rapid change in the potential of the tracks in any locality, which makes it difficult to prevent large potential differences between pipes and rails from developing locally, and the former to prevent the use of excessively long feeding distance, which, even with a small gradient, would permit the accumulation of large potential differences between pipes and tracks.

(*d*) *Manner of Specifying Voltage Limits.*—As to the manner of specifying the limiting voltages that should be allowed, there is a good deal of difference of opinion. Some prefer to specify a limit for momentary voltages, and others advocate restricting the maximum value for some definite short period, such as 10 to 30 minutes during the peak-load period, while many prefer to follow the practice of specifying an upper limit for the average voltage during the operating period. We have become convinced that the last plan is in general to be preferred.

Our investigations have shown that the actual amount of corrosion which takes place is much more nearly proportional to the average all-day load than it is to any short-time peak value. In fact, investigations made at the Bureau of Standards,[5] show that as the load increases and the current density is thereby increased the actual amount of corrosion does not increase as fast as the current increases. For this reason it is undesirable to place a heavy penalty on a high peak of short duration, provided the average current is small. This objection is avoided entirely by specifying the average value of the voltage instead of some short time peak-load value.

To specify a limiting value of voltage during from 10 to 30 minutes would probably not be a serious matter in the case of a congested city district, where the railway loads are comparatively steady and the load curve shows a comparatively flat maximum. In case of suburban or interurban lines operating an infrequent schedule, particularly where multiple car passenger trains and heavy freight trains are operated, any short-time voltage limitations will almost always impose upon the railway company a hardship that is altogether out of proportion to the benefits that could possibly result from such a method of defining the maximum.

In the case of interurban railway systems, any voltage limitations based upon momentary maximum values would be practically prohibitive, unless the voltage limit were placed so high as to be of no real value for general adoption. It seems best, therefore, that any voltage limitations that may be applied be based upon the all-day average value of the voltage rather than on any short-time period. Investigations have shown that if the polarity of the pipes reverses frequently, as, for example, every few minutes or oftener, the actual amount of corrosion which results is practically proportional to the algebraic average value of current due to the fact that for short periods of reversal the corrosive process is in large degree reversible. If, however, the frequency of reversal is very low, the reversal taking place once an hour, or at longer intervals, the corrosion increases and tends to become more nearly proportional to the average value of current during the time when the pipe is positive to earth, the average being of course reduced to a 24-hour basis.

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[5] Burton McCollum and K. H. Logan, "Electrolytic corrosion of iron in soils," Bureau of Standards Technologic Paper No. 25.

Owing to the uncertainty of the length of the periods of reversal that may occur under average operating conditions, it is best in fixing voltage limits in practice to base the limiting values on the 24-hour average value of voltage during those periods when the pipe frequently becomes positive to earth. In interpreting the significance of voltage readings actually taken, however, where the frequency of reversal is always approximately known, it is best to bear in mind that for periods of reversal of a few minutes or less the algebraic average affords a better criterion of the damage that will result than the arithmetical average.

A careful study of the local conditions in this country, in the light of the extended experience in European countries with the voltage limits that have prevailed there for many years, indicates that the average all-day voltage drop in the railway tracks under average conditions should be restricted to a value not exceeding about 2 to 4 volts, the lower value applying to localities such as business centers in large cities where the underground utilities are highly developed and of great value, and the higher value to those regions in which the utilities are developed to a lesser extent, such as the average residential districts in cities.

In very sparsely settled districts still higher voltage drops may be permitted, and in many cases, especially where tracks are on private right of way and substantially insulated from earth, thoughout their entire length the voltage limits may even be dispensed with altogether. Thus, in fixing regulations for any given city, some sort of a zone system is desirable, different voltage limits being prescribed for different zones, according to the value of the underground utilities and other local factors.

These all-day average values of 2 to 4 volts would, in the case of the majority of railway loads, correspond to an average during the maximum hour of from 3 to 10 volts, there being a greater variation in the values for the shorter than for the longer period. The average gradient corresponding to this over-all limit will depend in large measure on the means that are adopted for complying with the limitation and on the feeding distance. A study of the best methods available for reducing voltage drops indicates that the average 24-hour gradient at any point in the rail should under average conditions not be permitted to exceed about 0.3 to 0.4 volt per 1000 feet.

These limits of 0.3 to 0.4 volt per 1000 feet for the 24-hour period correspond roughly to 0.4 to 0.5 volt per 1000 feet for the 18-hour operating period. If the drop of potential on pipes or earth is made the basis of limitation, lower values would have to be used. Experience indicates that, on the average, over-all potentials and potential gradients in the earth should be maintained at about one-half the figures given above in order to insure the same freedom from electrolysis.

We do not wish to be understood as taking the view that the average voltage for the maximum hour or even half hour can not be made a satisfactory basis for voltage regulation. Experience has shown that either plan can be made to work out very well in practice. Recent investigations, however, show that the use of the longer period is a more rational basis of fixing voltage limits, since it gives a factor which is more nearly proportional to the actual danger involved than any other. Cases continually arise in the operation of street railway systems where local traffic congestion will cause very excessive voltage drops locally for short periods of from 5 to 15 minutes or longer, but these occur so infrequently that they have but slight effect on the average all-day values, and hence on the total damage from stray currents.

To adopt any rule which would limit these transient rises of voltage to very low values would involve an expense to the railway company which would be out of all proportion to the benefits that would accrue to the owners of underground utilities. On the other hand, if the voltage limit is placed high enough so that it can reasonably be applied to lines having very heavy transient loads, it would be altogether too high for other lines having comparatively steady loads. If the all-day average value is used, however, the cost of meeting the limit, as well as the degree of protection, will be independent of the character of the load on different lines.

As to the convenience of determination of the voltage limits prescribed there is little to choose between the two plans. Even if a short period be adopted, it will be necessary to use recording voltmeters, and records would have to be taken over practically the entire day to make sure that the limiting values were being recorded, and when the all-day record is at hand, the all-day average value can be obtained with practically the same facility as the average for shorter periods. The all-day average value of voltage would therefore appear to be the most natural and logical criterion to use as the basis of voltage regulations. Whatever method may be ultimately adopted for defining any maximum allowable limits that are to be prescribed for any particular locality, extended experience both in this and in foreign countries shows that the average values must not greatly exceed the figures mentioned, provided reasonable and permanent protection is to be accorded to the underground pipe system.

5. GENERAL SCOPE OF REGULATIONS

(*a*) *Voltage Limitations.*—From the foregoing it will appear that one of the most essential things to be incorporated in electrolysis regulations is an appropriate limitation of the potential drops in the railway track network, or in the earth and pipe systems, and that such limits should be applied in the case of railway tracks to both the over-all potential drops between remote parts of the system and also to potential gradients in relatively short portions of the track network, the former being necessary to guard against the accumulation of large potential differences which might occur even with low gradients, provided the feeding distances are very long, and the latter to prevent the very rapid change in the voltage of the track in any portion of the system which might give rise to bad local conditions even though the over-all potentials were kept comparatively small.

In fixing voltage limits for regulation it is desirable to specify the manner in which the voltages are measured and potential drops computed. In determining the potential gradients the voltage drop on a distance of 1000 feet is generally better than a much shorter length. This length is long enough to give a fair average condition over a considerable length of track, and at the same time short enough to prevent any serious accumulation of potential difference at any point, provided the limits mentioned above are substantially complied with. In calculating the potential gradient it is best to measure the distance in an air line between the terminal points, provided the region crossed by this line is occupied by pipe networks; but if the pipe networks follow an indirect course, measurements should be made by way of the pipes.

(*b*) *Potential Wires.*—In order to facilitate the determination at any time of the voltage drop, it is very important that permanent potential wires be installed running from a suitable terminal board at some central point and connected to the tracks or pipes at those points between which potential measurements are to be made. These should always be run to the more outlying points and also to the point in the system of approximately lowest potential so that the maximum over-all potential drops can be directly measured. It is desirable also in most cases to have some wires run to intermediate points, so that any high potential drop that may be observed can be approximately localized by measurements with the potential wires. Such wires may either be especially installed for the purpose of taking potential measurements, or wires for this purpose may be leased from a telephone company. When satisfactory terms can be arranged, the leasing of wires is preferable, since the maintenance of these wires would, in general, be less than of special wires run separately for this purpose.

In view of the fact that the purpose of the potential wires is not primarily for the protection of the pipe systems but rather to supply information to all parties concerned as to the conditions which exist, it seems preferable that the expense of installing and maintaining or of leasing such potential wires should be borne jointly by all of the utility companies directly concerned in the electrolysis mitigation problem. If this were done, the cost to any particular company would be practically negligible and it would remove any material objection which the railway company might otherwise have to the installation of such potential wires. Graphic voltmeters should also be provided for measuring and recording the potential differences required.

(*c*) *Connections Between Tracks and Pipes.*—Metallic connections between underground metallic structures and the street railway tracks should never be permitted at any point where the pipes might become negative to the tracks and such ties deliver current into the pipe system. Such connections are sometimes advocated as a means of reducing voltage drops in the negative return, but the objections to such procedure are too obvious to be discussed here. It is not desirable in general to prohibit all metallic connections between pipes and railway negative return in the regions near the power stations, although in general in city systems such connections are not desirable, except in the case of lead cable systems where properly restricted drainage may be used. There are, however, special cases in which it might be desirable to install such ties on pipe systems, and this should not be entirely prohibited by the regulations.

(*d*) *Interconnection of Tracks.*—Wherever two or more railway systems operate in the same territory it is of the greatest importance that the tracks should be electrically connected together at all intersections and such interconnection should be required by regulations. In special cases where tracks, either of the same or different railway lines, parallel each other for a considerable distance, such as half a mile or more, and where the tracks are only a block or so apart, it is important that occasional crossties between the lines be installed to prevent wide fluctuations of voltage between them. This would be a special provision designed to meet local conditions rather than a general rule.

(*e*) *Track Maintenance.*—If the voltage drops in the tracks be limited by regulation and if a sufficient number of potential wires are installed not only to the remote points of the system, but also to intermediate points so that the potential gradients on practically all sections of the track of lengths from 1000 to 3000 feet can be readily measured, it would not appear desirable to superpose on this any additional regulation in regard to track maintenance, leaving that matter entirely to the railway company. If, however, potential wires are connected only to the remote portions of the network, they would not give sufficient data in regard to electrolysis conditions at intermediate points, and in such cases it would be desirable to have some sort of regulation covering track maintenance. This might take the form of a rule requiring periodic tests and reports of the condition of the track bonding, and definitions regarding what may be considered a good or bad bond.

Practice in regard to the latter point varies considerably in this country, but in general where the resistance of a joint (including 3 feet of rail) exceeds the resistance of a length of from 6 to 10 feet of rail the joint is considered defective. Cross bonding between tracks should also be required at frequent intervals.

The best practice in this country at the present time calls for cross bonds at intervals of from 200 to 500 feet of track, according to traffic conditions, and bonding at shorter distances is required where the traffic is heaviest. Such bonds should be designed to carry the maximum current to which they can be subjected in use.

(*f*) *Exemptions.*—Where railway lines operate in a territory remote from pipe systems exemptions from stringent regulations should generally be made. The German regulations exempt entirely railway lines which operate at a distance exceeding 200 meters (650 feet) from any pipe systems. Such an exemption undoubtedly involves no danger to the underground structures. Where the railway line is so constructed that the rails are practically insulated from the earth, such, for example, as a railway line on a private right of way on which the rails are set up on wooden ties entirely out of contact with the earth, exemption from rigorous voltage regulations regarding track potentials should also be made.

(*g*) *Insulated Negative Feeders.*—If the regulations prescribe certain specific and definite voltage limitations that must be complied with, it will not be best to specify the manner in which such regulations are to be met. In order, however, to make it readily possible to further improve conditions at a later date, if such improvement should be found necessary, and to accomplish this without any appreciable extra cost to the railway companies, it would be well to require that in any future construction wherever negative feeders are installed at all they should be installed as insulated feeders in such a way that they may, when necessary, be converted into what has been defined in this paper as an insulated negative feeder system. The insulation of negative feeders in this way is practically no more expensive than the installation of uninsulated feeders, so that no hardship would be imposed on the railway company by such requirements; on the other hand, in case future experience showed it to be necessary to still further reduce voltage drops, it would be a decided advantage to the railway company to the have feeders installed in this way.

6. RESPONSIBILITIES OF OWNERS OF UNDERGROUND UTILITIES REGARDING ELECTROLYSIS

In considering the subject of regulations for the mitigation of electrolysis, it should be borne in mind that while the railway companies are chiefly responsible for reducing stray currents to as low values as are commercially practicable, the owners of underground utilities also must be considered to have certain responsibilities, particularly in so far as new construction work is concerned in territory already occupied by electric railways.

There are a number of things that pipe and cable owning companies can do at a very slight additional expense that will go very far to reduce electrolysis trouble, provided such measures are taken at the time the pipes or cables are installed. For example, in new work or repairs, pipe lines should be laid as far as possible from railway tracks. Where the density of service connections is sufficient to justify the use of two mains, one on each side of the street, these should be laid down in order to eliminate the necessity for running services across under the railway tracks. This is quite common practice in many places where the utilities are highly developed, and it could frequently be extended in many instances with considerable improvement in local electrolysis conditions. Further, in laying new mains or repairing old ones, it is very simple and inexpensive to install a sufficient number of insulating joints largely to reduce stray currents in that portion of the pipe network, and such construction should be encouraged in every practicable way.

Wherever it is necessary to run service pipes across the street under railway tracks, care should be taken either to lay them as far as practicable below the tracks or else to provide substantial insulation between the service pipe and the track or between the service and the main by means of insulating joints; the latter will generally be found cheapest and most effective.

7. LIMITATION OF PIPE DRAINAGE

In view of the fact that excessive drainage of current from one pipe system may set up a condition of serious danger in a neighboring system, measures should be taken to so restrict the drainage of current from any one underground metallic structure that it will not be maintained at a potential sufficiently lower than surrounding structures to cause any serious injury thereto.

8. ADMINISTRATION OF REGULATIONS

Where regulations governing electrolysis mitigation are necessary, they should preferably be enacted and administered by State authority, where the necessary administrative machinery is available. In the absence of such administrative authority, however, the cities in which the utilities operate, should take the initiative. The Federal Government, while competent to carry out engineering investigations bearing on the problem as it is now doing, can not undertake to prescribe or administer regulations. Where State public utility commissions are in existence, they constitute the most logical and competent authority to deal with this subject. Such State commissioners are not only able to deal with the subject in a broader and more comprehensive way than the majority of local bodies, especially in smaller cities, but their freedom from the influences of local interests will often enable them to deal more wisely and justly with all companies involved.

It is in the highest degree desirable that regulations be made as few and as simple as possible, to the end that the various utilities concerned may enjoy the greatest freedom of action consistent with safety to the underground structures.

The present apparent necessity for regulations governing this subject is due to the lack of cooperation in the past between the railway companies and the owners of underground utilities. If the various interests concerned, and particularly the railway companies, would show a greater disposition than they have commonly done to meet the issue, and instead of practically ignoring the subject, as has been too often done, would treat the matter as one of the engineering problems connected with the operation of street railways, the need for stringent regulations would be largely eliminated with advantage to all concerned. In the absence of such a far-sighted policy, however, compulsory and perhaps more or less burdensome regulations will become inevitable.

VI. SUMMARY

Among the more important conclusions brought out in the foregoing paper are the following:

1. The electrolysis problem was for a long time neglected in America, and partly as a result of this, is now more serious than in those European countries which early met it by Government regulations. During the last few years, however, much greater attention is being given to this subject by railway companies generally.

2. Electrolysis may give rise to a number of different classes of injury, such as fires, explosions, and damage to concrete structures. However, the damage from these effects is in the aggregate relatively small. By far the greater portion of the damage due to electrolysis is that arising from corrosion of underground pipes and cables. In particular, electrolytic damage to concrete structures is to be feared only where voltage conditions are exceptionally severe, or in the case of comparatively low voltages when salt has been added to the concrete either during or after construction.

3. In general, those remedial measures that are applicable to pipe systems should be regarded as secondary means of mitigation of electrolysis trouble, the principal reliance being proper construction and maintenance of the railway return circuit. In special cases, however, mitigative measures may be applied only to the underground structures.

4. Of the mitigative measures applicable to pipes only a few of those that have been advocated have found much application. The two most commonly applied are the installation of insulating joints and the use of pipe drainage. Both these methods are valuable under certain conditions, the former particularly where new pipes are being laid and the latter for application to isolated pipe systems without insulating joints and where no other underground utilities are present to cause complications. In most cases, however, these systems should be restricted to use as auxiliary means of protection, after reasonable precautions have

been taken to reduce potential drops in the tracks to as low values as are economically practicable. In any case where pipe drainage is used, the drainage should be through the medium of insulated feeder systems, so adjusted as to take the minimum possible current from the pipes at all points.

5. Of the methods applicable to railways the most important of those which have been thoroughly tried out are the adequate maintenance of track bonding, the use of a proper number and location of power houses or substations, and, where the carrying capacity of the rails is not sufficient to return current to stations without excessive drop, the use of insulated negative feeders for the return of such current, these latter being much more economical than uninsulated feeders where large reductions of potential drop are required. The three-wire system has proved effective in relieving electrolysis and should prove satisfactory from the electrolysis standpoint where operating conditions are favorable to its use. Thus far, however, too little experience has been had with this system to justify more than tentative conclusions.

6. Such remedial measures as have been adopted in this country have usually been applied to the pipes, and in general they have proven much less effective than measures used in certain foreign countries where regulations limiting voltage drops in the negative return have long been in effect and have been accompanied by substantial freedom from electrolysis troubles. Experience both here and abroad indicates that such limitation of voltage drop is necessary to a satisfactory solution of the problem.

7. In defining the voltage limitations either the all-day average value or the average value for a period not less than one-half hour may be used; the former, however, is preferable, since it affords the best criterion of the actual danger involved and is also more satisfactory from the standpoint of the railway companies. A shorter period than half an hour is too short to give a satisfactory basis for voltage regulations that are to be applied to the railway systems.

8. In fixing voltage limitations some plan analogous to the zone system should be adopted, the voltage limits prescribed for the various zones being determined largely by the degree of development of the underground utilities in the various zones.

9. The voltage drops either in the tracks or in the pipes, and earth may be used as the basis of fixing limitation, but in general the latter is to be preferred.

10. Under most conditions over-all voltages in railway tracks should be limited to about 2 to 4 volts, and the potential gradients should in general be restricted to about 0.3 to 0.4 volt per thousand feet, these figures being all-day average values, or to corresponding values based on averages for a period of not less than half an hour. The higher over-all voltage limit will generally apply to the longer feeding distance and outlying districts, while the higher potential gradient limit can be permitted where feeding distances are relatively short. Potential drops on pipe systems should be, roughly, half of these figures.

11. In order that ready determination of voltage drops can be made at any time, potential wires should be installed running from some central point to selected points on the railway or pipe networks. These points should include the points of approximately highest and lowest potential, and preferably also some intermediate points.

12. Exemption from any regulations regarding track voltages should be made in special cases as set forth in this paper, where local conditions make it improbable that any serious damage would result.

13. Any regulations governing electrolysis mitigation should be made to apply not alone to the railway system, but should also define the responsibilities of the owners of underground utilities, since the latter can often contribute materially to the diminution of the trouble at a practically negligible cost.

WASHINGTON, April 9, 1915.

APPENDIXES

APPENDIX 1.—EXTRACT FROM PAPER ON "MEANS FOR PREVENTING ELECTROLYSIS OF BURIED METAL PIPES"[a]

* * * Having referred to the method of preventing electrolysis, which has been employed on a portion of the pipes in Boston and in some other American cities for several years, and to some of the erroneous ideas on the subject, we may now present the outline for another method of minimizing the danger. No description of this plan has ever before appeared in print. It is furthermore attractive as lying entirely within the power of the railway companies to adopt. It is not excessively expensive and it does not involve connections with other companies' property, nor the mutual cooperation of cities or corporations. By this method the tracks of the railway will also be preserved from electrolytic action.

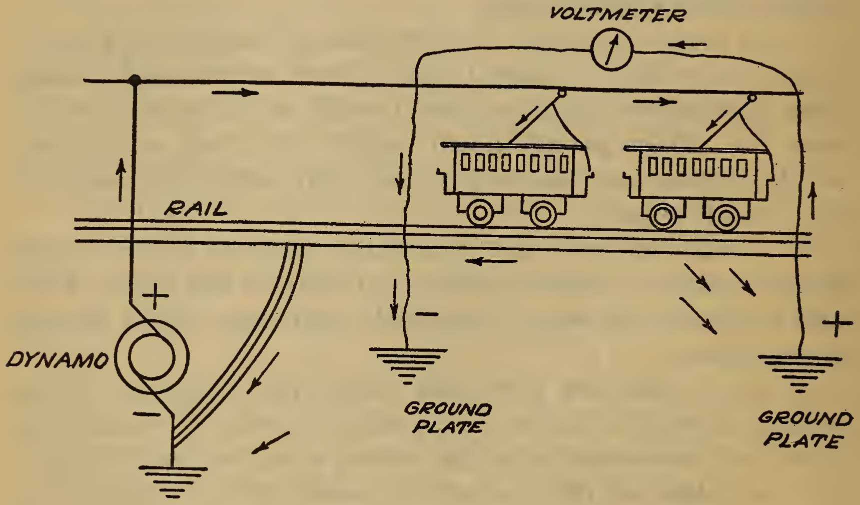

FIG. 41.—*Diagram showing the difference in potential along an electric railway*

In order to bring the principle clearly before the reader, the writer would call attention to a fact generally known, but often ignored. In all cities where electric railways operating the single-trolley system are in use, and especially where trouble from electrolysis has been discovered, it is found that the earth in one section of the city has a different electrical condition from that in certain other sections. If an insulated wire, having included in its length a suitable galvanometer or voltmeter, is extended between a ground plate located near the railway power house and another ground plate located a mile distant from the first plate, as shown in the diagram marked Fig. 1 [identified as Fig. 41 in this publication], a difference of potential will be found to exist between these plates. If the dynamo is connected with its positive pole to the trolley, the ground plate situated at the greater distance will be positive to the plate near the power house.

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[a] By Isaiah H. Farnham, published in Cassier's Magazine for August, 1895.

Some of the fire underwriters recognize this difference of potential as a danger, and they attempt to rule against it. The writer has known such difference of potential to reach 50 volts and more. The earth in the distant territory is, so to speak, saturated with positive electricity, while near the station it is being "pumped out" or made negative by the dynamo. This want of a level, or balance, in the electrical condition of the earth, leads to a flow of the current from the higher to the lower electrical level, much as would occur if water should replace the electricity. In flowing, the electricity finds its way into pipes and cables, and, on leaving them at the lower level, causes the electrolytic action.

Fig. 2 [identified as Fig. 42 in this publication], on the next page, will, by analogy, fairly illustrate this want of electrical balance or level in the earth. The line A represents the surface of the earth; B, the surface of a flood of water produced by a heavy rain, and flowing to a low plane where a pump is drawing the water from the earth in a limited district.

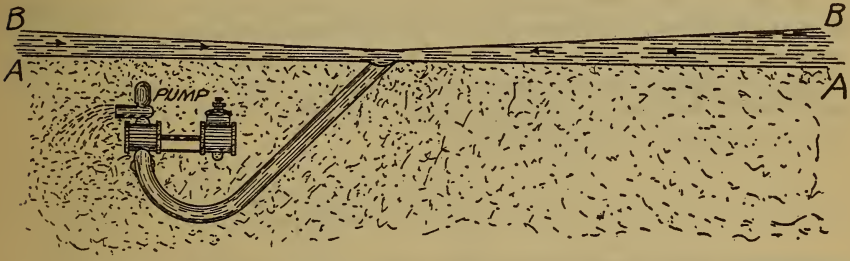

Fig. 42.—*Diagram illustrating the want of electrical balance in the earth*

If, now, we can preserve a level or balance in the electrical condition throughout the city, or, in other words, prevent a difference of potential, there will be no disposition for a current to flow from one portion of the city to another. It is the purpose in the plan now proposed to accomplish this equalization of potential as nearly as possible. To illlustrate by the water analogy, Fig. 3 [identified as Fig. 43 in this publication] shows the flood of water being pumped from many points on the surface of the earth by pipes of proper size, so that there is substantially no difference of water level, and therefore no flow from one distant point on the earth to another. A comparison of this figure with the one above it will render the point clearer.

As may be anticipated by a study of the principles already set forth, the new method consists in extending from the negative or rail side of the dynamo an insulated return wire, either on poles or underground, throughout the entire length of the railway, including all cross-town or branch tracks. This return wire is to be of such size as to properly carry the current and to maintain the return path at a comparatively low resistance. For a track extending 3 miles in any one direction from the power house a No. 0000 copper wire would give a resistance of but 1 ohm from the most distant point. Two such wires, about one-third inch in diameter each, would not seem excessive in cost, and would render the maximum resistance but one-half ohm from car to power house.

In large railway systems a still heavier main return may be employed. From this general return wire or system of wires frequent connections would be extended to the track system, say one at every other pole (200 feet). Let these connections between the general return wire and the rails be of such size, or shape, as to cause the resistance from the rail at the nearest point to the power house to be the same, no more nor less, than from the most distant rail connection to the power house; that is, with such a system, if the resistance of the circuit from the rail, 3 miles distant, to the power house is one-half ohm, the resistance from any other point along the route of the track shall also be one-half ohm to the power house. Allow no ground connection on the dynamos and no direct connection to the rails without the proper resistance. Fig. 4 [identified as Fig. 44 in this publication] roughly represents such a system. It should be understood that the rails are to be suitably bonded under this, as other systems using the rails for a portion of the electric circuit.

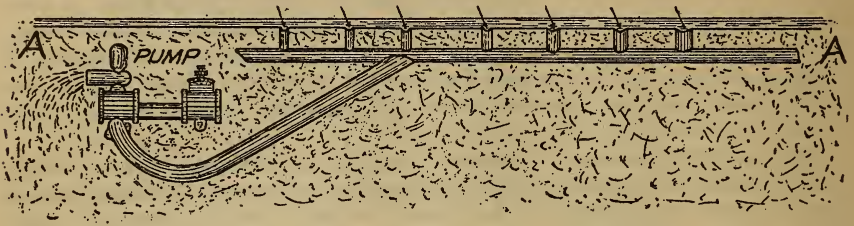

FIG. 43.—*Diagram illustrating an example of electrical balance*

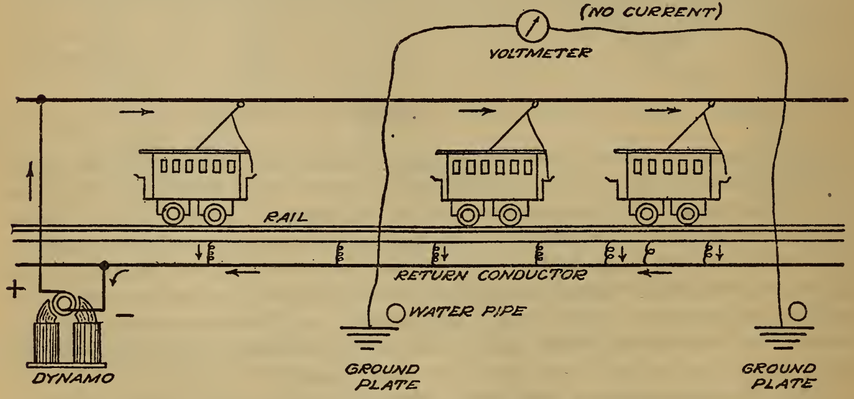

FIG. 44.—*A system with which electrolysis of buried pipes is avoided*

If, now, we imagine an approximately uniform distribution of cars, there can be no rise or fall of potential in the earth except at the very limited areas between the several points where the rails are connected to the general return wire system. Cars are not, of course, equally distributed over a city, and, therefore, perfect results can not be reached by carrying out this plan, but to adopt it is certainly working in the right direction, and as the distribution of cars approximates uniformity, the advantages of the system will approach the maximum. On the other hand, with the present usual manner of connecting the return wires to the tracks there never can be a condition where a difference of potential will not exist between different sections of a city, no matter how nearly perfect the rail system is constructed as a return conductor, and, therefore, there can be no elimination of current passing from a higher to a lower potential throughout a city; and, of course, as the currents pass through the earth, pipes are brought into the path, and constitute a portion of the electric conductor, with all the possibilities of electrolysis wherever, from a poor joint or for other reasons, the currents leave the pipes for the damp earth on their way to the negative side of the dynamo.

This system of returning the railway current will accomplish several desirable ends: (1) It will allow but very little current to enter the earth and flow therein; (2) the current through the earth being minimized, electrolysis will to that extent be prevented; (3) having by this means reduced the danger of electrolysis to small proportions, it will be comparatively easy to take care of the remaining danger, if such be found, by resorting to the means described in the previous paper; (4) in addition to practically overcoming the danger of electrolysis, the annoyance to telegraph, telephone, burglar alarm, and other grounded circuits, due to difference of potential in different sections of a city, will be incidentally removed.

The equi-potential return system just described has so far been tried in a New England city as to indicate practically that the benefits claimed for it may be confidently expected.

APPENDIX 2.—PUBLICATIONS OF THE BUREAU OF STANDARDS RELATING TO ELECTROLYSIS

Technologic Paper No. 15: Surface Insulation of Pipes as a Means of Preventing Electrolysis; by Burton McCollum and O. S. Peters.

Technologic Paper No. 18: Electrolysis in Concrete; by Dr. E. B. Rosa, Burton McCollum, and O. S. Peters.

Technologic Paper No. 25: Electrolytic Corrosion of Iron in Soils; by Burton McCollum and K. H. Logan.

Technologic Paper No. 26: Earth Resistance and its Relation to Electrolysis; by Burton McCollum and K. H. Logan.

Technologic Paper No. 27: Special Studies in Electrolysis Mitigation, No. 1; by Dr. E. B. Rosa and Burton McCollum.

Technologic Paper No. 28: Methods of Making Electrolysis Surveys; by Burton McCollum and G. H. Ahlborn.

Technologic Paper No. 32: Special Studies in Electrolysis Mitigation, No. 2; by Dr. E. B. Rosa, Burton McCollum, and K. H. Logan.

Technologic Paper No. 52: Electrolysis and Its Mitigation; by Dr. E. B. Rosa and Burton McCollum.

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27. Special Studies in Electrolysis Mitigation (55 pp.) *E. B. Rosa and Burton McCollum*
29. Variation in Results of Sieving with Standard Cement Sieves (16 pp.) *R. J. Wig and J. C. Pearson*
30. The Viscosity of Porcelain Bodies (9 pp.) *A. V. Bleininger and Paul Teetor*
31. Some Leadless Boro-Silicate Glazes Maturing at about 1,100° C. (21 pp.) *E. T. Montgomery*
32. Special Studies in Electrolysis Mitigation, No. 2. Electrolysis from Electric Railway Currents and Its Prevention—Experimental Test on a System of Insulated Negative Feeders in St. Louis (34 pp.) *E. B. Rosa, Burton McCollum, and K. H. Logan*
33. The Determination of Carbon in Steels and Iron by the Barium Carbonate Titration Method (12 pp.) *J. R. Cain*
34. Determination of Ammonia in Illuminating Gas (23 pp.) *J. D. Edwards*
35. Combustion Method for the Direct Determination of Rubber (11 pp.) *L. G. Wesson*
36. Industrial Gas Calorimetry (150 pp.) *C. W. Waidner and E. F. Mueller*
37. Iodine Number of Linseed and Petroleum Oils (17 pp.) *W. H. Smith and J. B. Tuttle*
38. Observations on Finishing Temperatures and Properties of Rails (63 pp.) *G. K. Burgess, J. J. Crowe, H. S. Rawdon, and R. G. Waltenberg*
39. Analysis of Printing Inks (20 pp.) *J. B. Tuttle and W. H. Smith*
40. The Veritas Firing Rings (10 pp.) *A. V. Bleininger and G. H. Brown*
41. Lead Acetate Test for Hydrogen Sulphide in Gas (46 pp.) *R. S. McBride and J. D. Edwards*
42. Standardization of No. 200 Cement Sieves (51 pp.) *R. J. Wig and J. C. Pearson*
43. Hydration of Portland Cement (71 pp.) *A. A. Klein and A. J. Phillips*
44. Investigation of the Durability of Cement Drain Tile in Alkali Soils *R. J. Wig, G. M. Williams, S. H. McCrory, E. C. Bebb, and L. R. Ferguson*
45. A Study of Some Recent Methods for the Determination of Total Sulphur in Rubber (16 pp.) *J. B. Tuttle and A. V. Bleininger*
46. A Study of the Atterberg Plasticity Method (18 pp.) *Charles S. Kinnison*
47. Value of the High-Pressure Steam Test of Portland Cement (34 pp.) *R. J. Wig and H. A. Davis*
48. An Air Analyzer for Determining the Fineness of Portland Cement (74 pp.) *J. C. Pearson and W. H. Sligh*
49. Emergent Stem Correction for Thermometers in Creosote Oil Distillation Flasks 21 pp.) *R. M. Wilhelm*
50. An Investigation of Fusible Tin Boiler Plugs (7 pp.) *George K. Burgess and Paul D. Meri*
51. Electrolysis and Its Mitigation (40 pp.) *E. B. Rosa and Burton McCollum*
52. Electrolysis and Its Mitigation (143 pp.) *E. B. Rosa and Burton McCollum*

[A complete list of Scientific Papers, Circulars, and miscellaneous publications may be obtained free of charge on application to the Bureau of Standards, Washington, D. C.]